# On the high-energy IceCube neutrinos


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IFIC, CSIC-U. Valencia


Perspectives in astroparticle physics from high energy neutrinos

Naples, June 26, 2017

# New physics

effects on the energy spectrum

effects on the angular distribution

effects on the flavor composition

# Why do we care about flavor?

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It carries information about the mechanism of production...

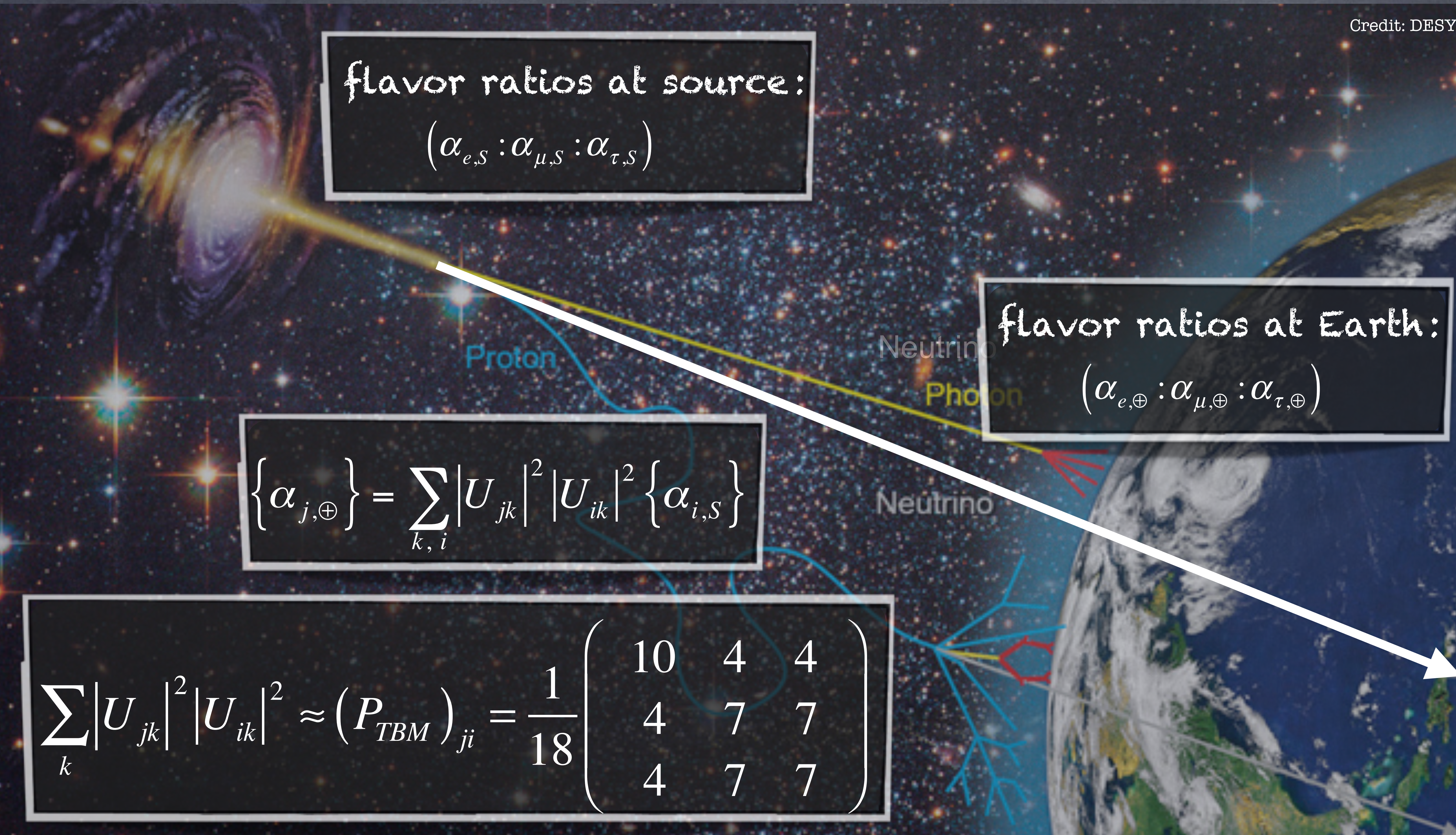
# Why do we care about flavor?

It carries information about the mechanism of production...

...but also about the way neutrinos propagate from the sources to the detector

Exotic physics could produce deviations from the standard expectations

# Standard cosmic propagation




flavor ratios at source:

$$\left(\alpha_{e,S} : \alpha_{\mu,S} : \alpha_{\tau,S}\right)$$

flavor ratios at Earth:

$$\left(\alpha_{e,\oplus} : \alpha_{\mu,\oplus} : \alpha_{\tau,\oplus}\right)$$

$$\left\{\alpha_{j,\oplus}\right\} = \sum_{k,\,i} \left|U_{jk}\right|^2 \left|U_{ik}\right|^2 \left\{\alpha_{i,S}\right\}$$

$$\sum_k \left|U_{jk}\right|^2 \left|U_{ik}\right|^2 \approx \left(P_{TBM}\right)_{ji} = \frac{1}{18}\begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

# Flavor ratios at source and Earth

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \qquad \mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

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**Pion sources** $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:2:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (1:1:1)$

**Muon damped sources** $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (0:1:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (4:7:7)$

**Muon sources** $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:1:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (14:11:11)$

**Neutron sources** $\left(\nu_e : \nu_\mu : \nu_\tau\right)_S = (1:0:0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau\right)_\oplus = (5:2:2)$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

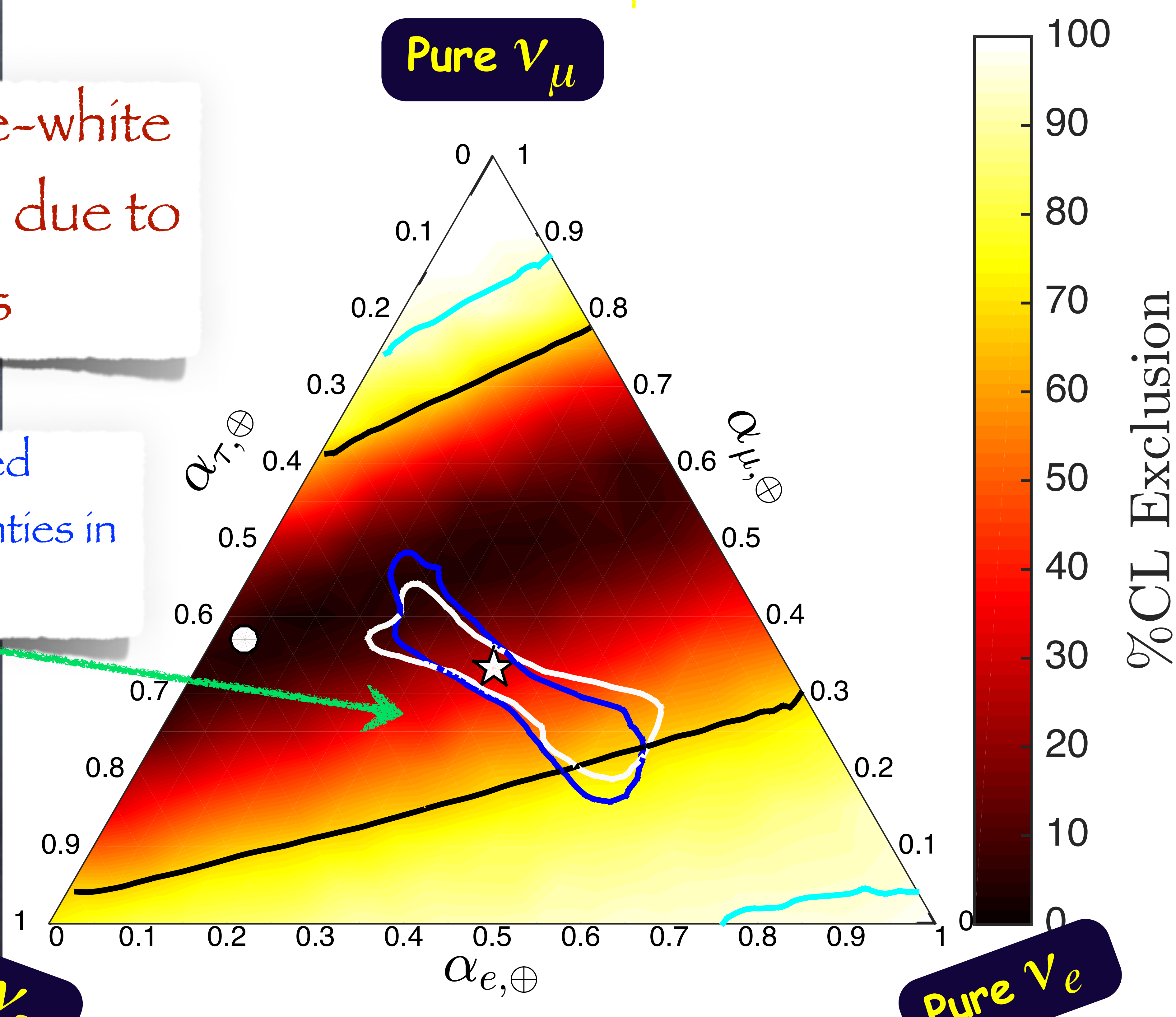
# Flavor triangles

**4-year data**

$E_{dep} = [10\text{ TeV}, 10\text{ PeV}]$

If outside the blue-white regions, it must be due to new physics

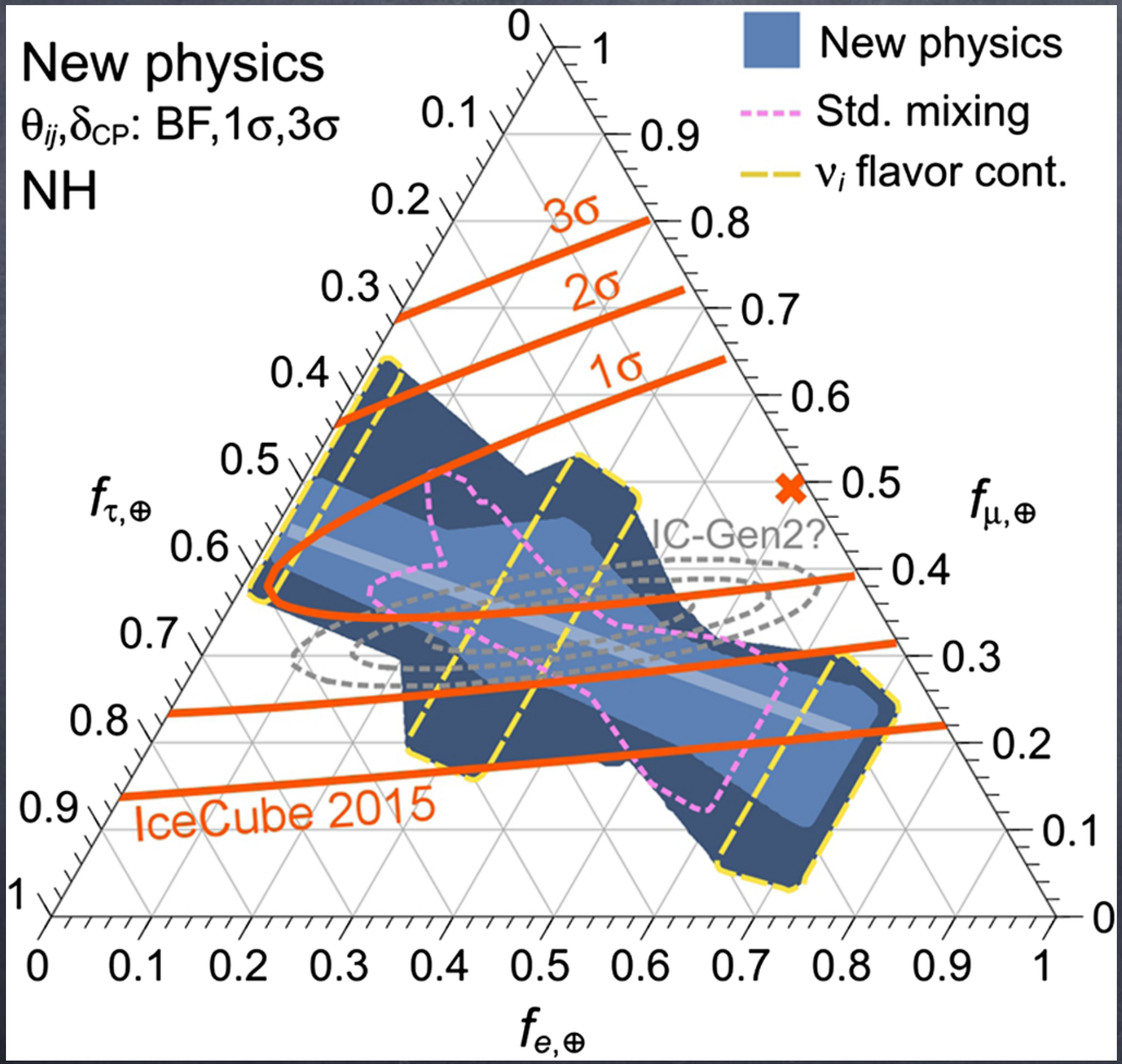
Flavor ratios with averaged oscillations and uncertainties in mixing parameters




A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# INCOHERENT MIXTURE OF MASS EIGENSTATES

neutrino decays, pseudo-Dirac neutrinos...
or neutrino secret interactions, Planck-scale decoherence




Yet, the flavor triangle is not fully covered!

More extreme scenarios are required!

M. Bustamante, J. F. Beacom and W. Winter, Phys. Rev. Lett. 115:161302, 2015

# MORE EXTREME SCENARIOS

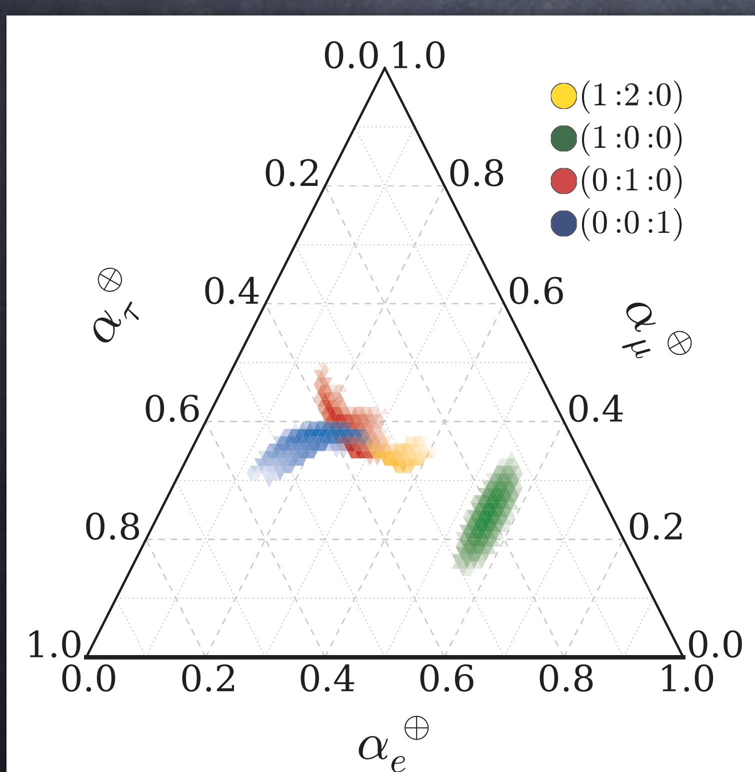
Using effective operators:
general evolution hamiltonian

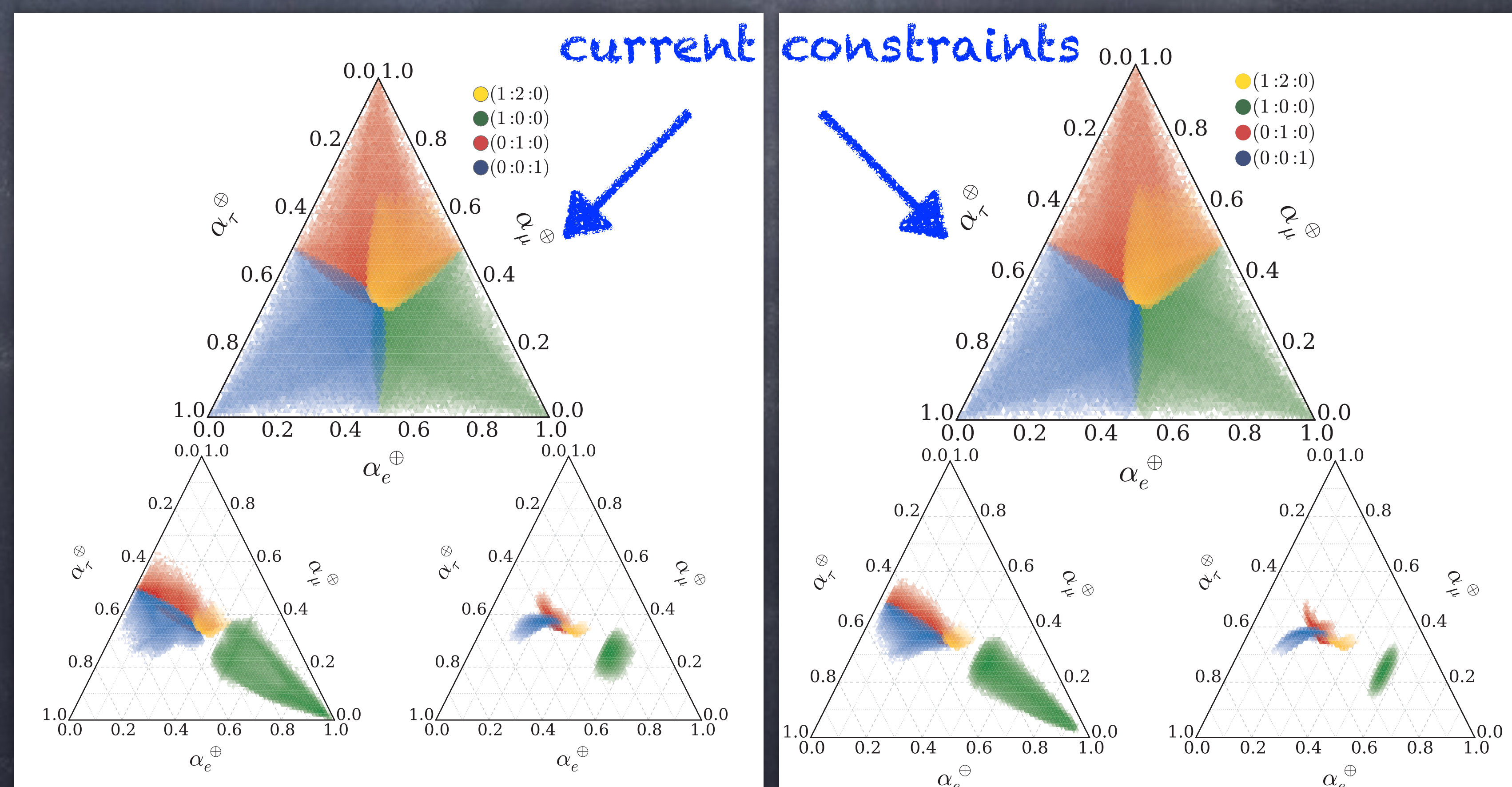
flavor structure of new physics

$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_n \left( \frac{E}{\Lambda_n} \right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger$$

**n=0** : neutrino couplings to spacetime torsion, CPT-odd Lorentz violation, NSI

**n=1** : CPT-even Lorentz violation, equivalence principle violation



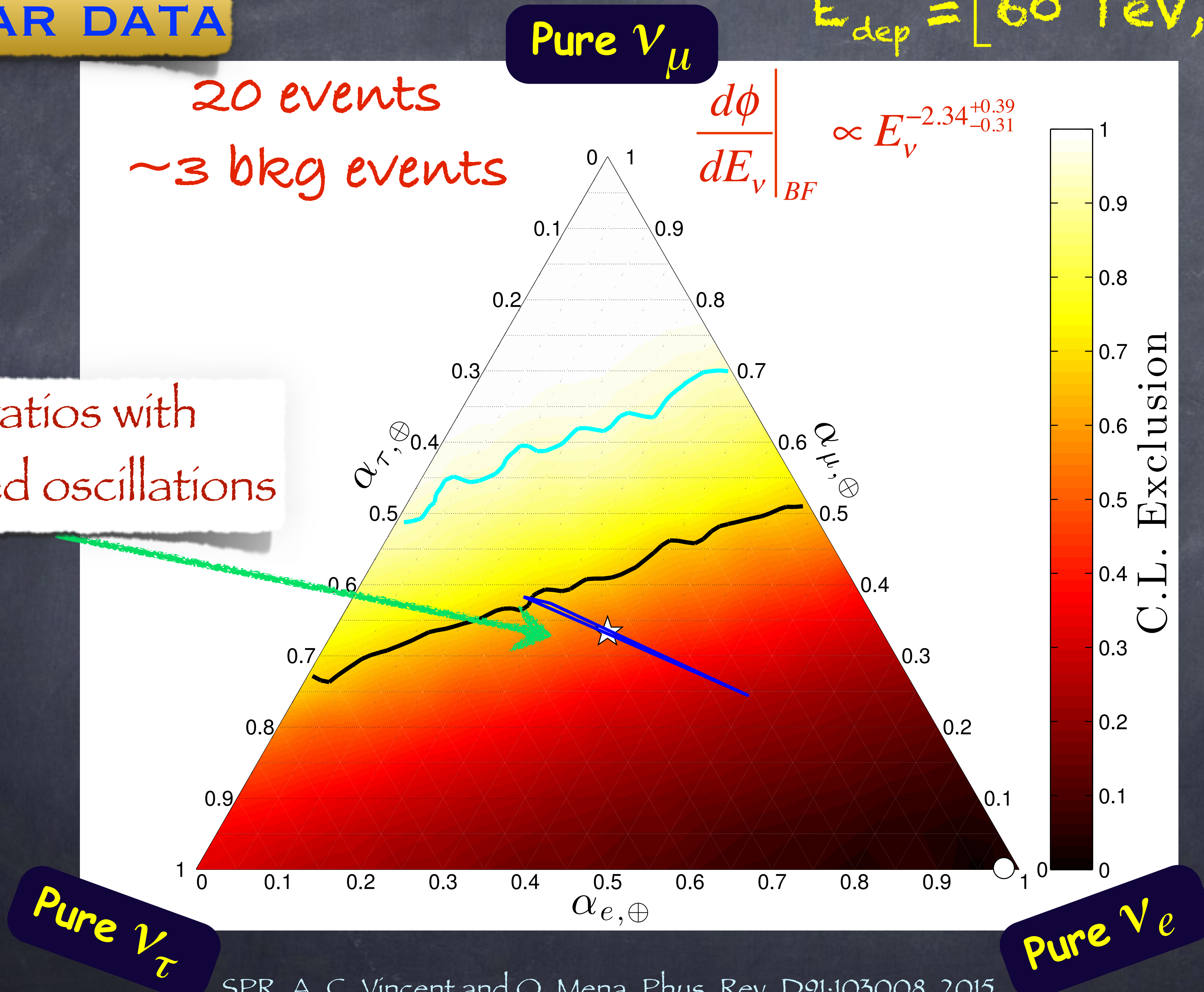




C. A. Argüelles, T. Katori and J. Salvadó, Phys. Rev. Lett. 115:161303, 2015

# Effect of high-energy cut

3-year data

$E_{dep} = [60 \text{ TeV}, 3 \text{ PeV}]$



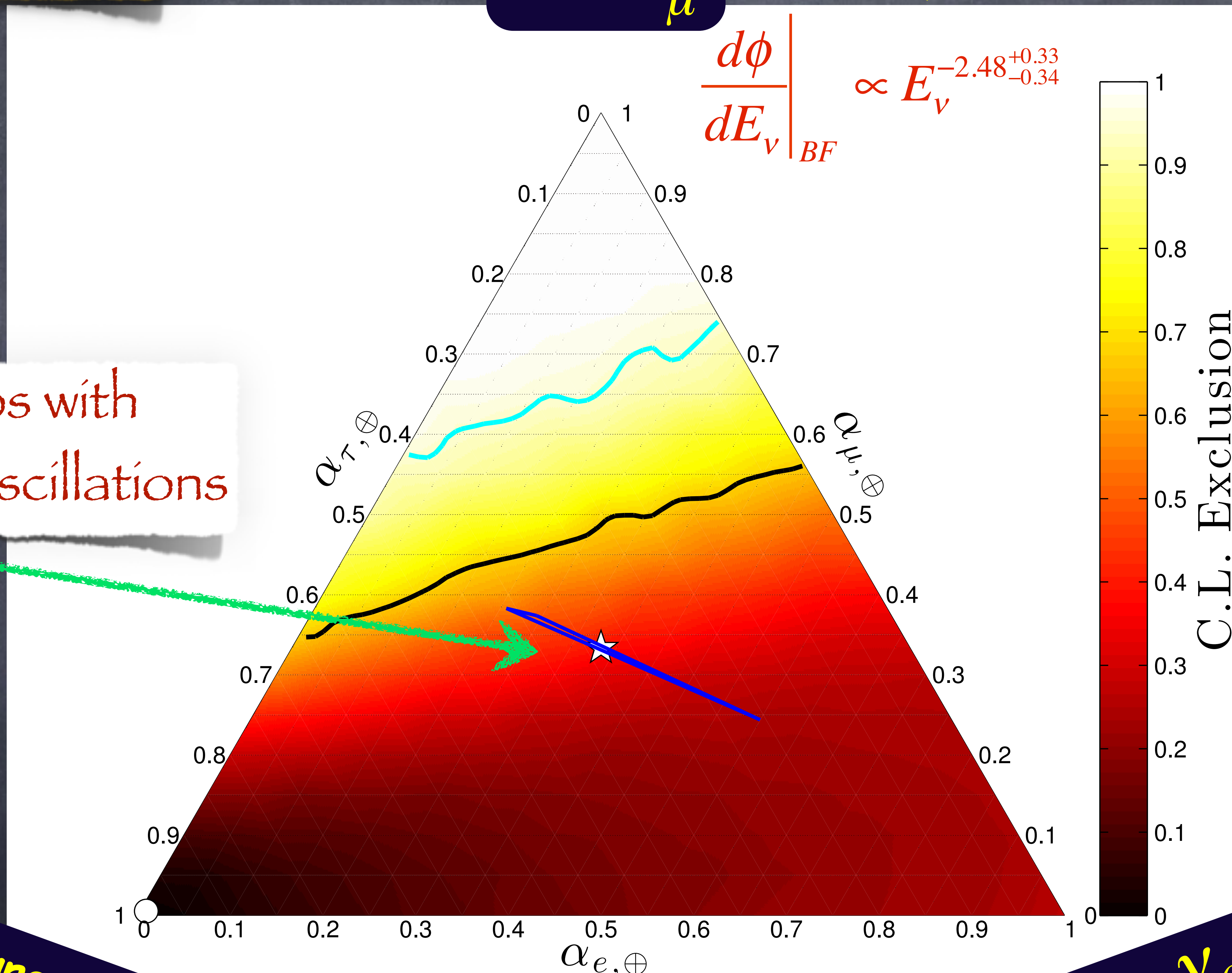

SPR, A. C. Vincent and O. Mena, Phys. Rev. D91:103008, 2015

# Effect of high-energy cut

**3-year data**

$E_{dep} = [60 \text{ TeV}, 10 \text{ PeV}]$

Pure $\nu_\mu$




Flavor ratios with averaged oscillations

Pure $\nu_\tau$

Pure $\nu_e$

SPR, A. C. Vincent and O. Mena, Phys. Rev. D91:103008, 2015

# Effect of high-energy cut

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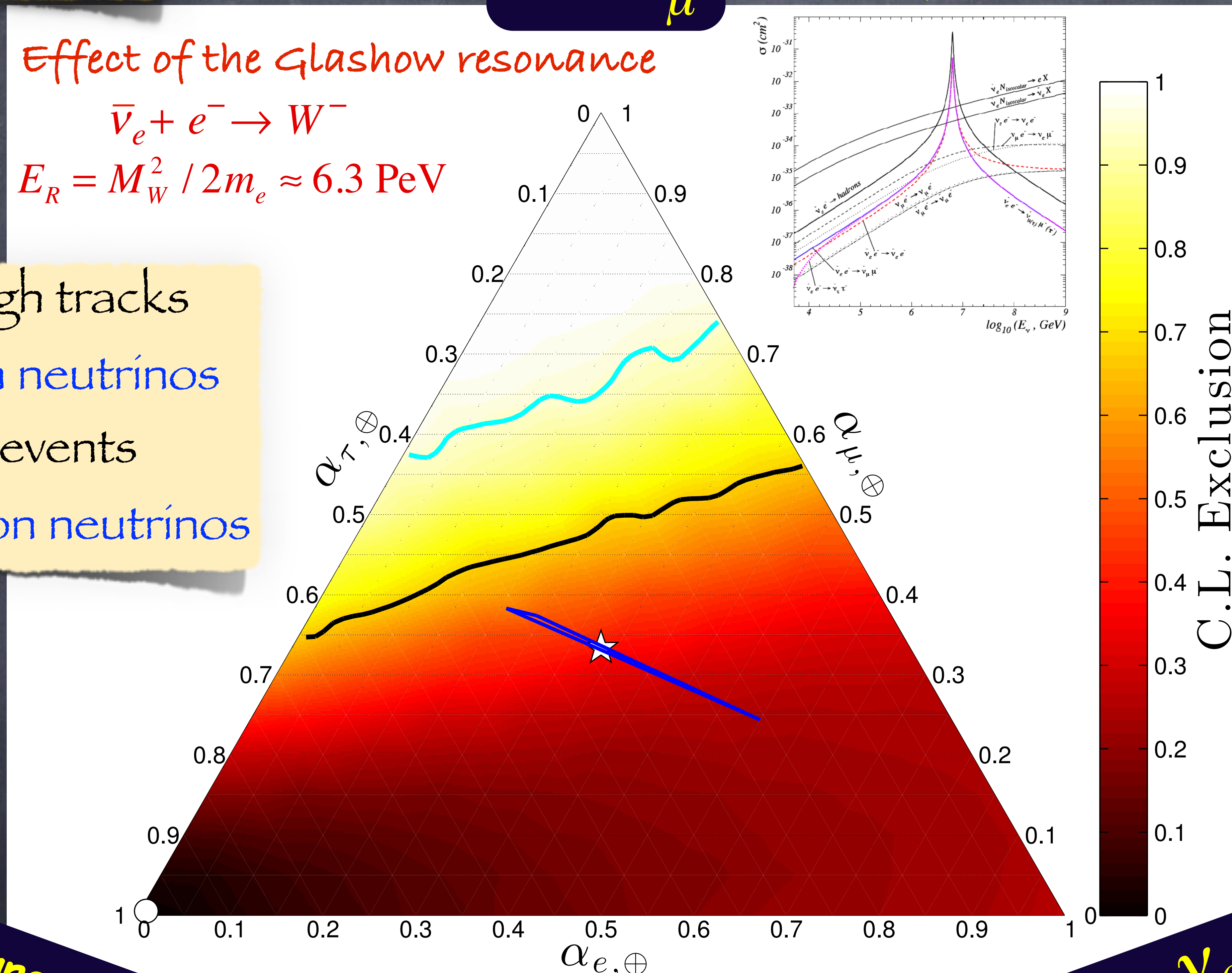


Not enough tracks
→ no muon neutrinos
No GR events
→ no electron neutrinos

SPR, A. C. Vincent and O. Mena, Phys. Rev. D91:103008, 2015

# Effect of Spectral Break

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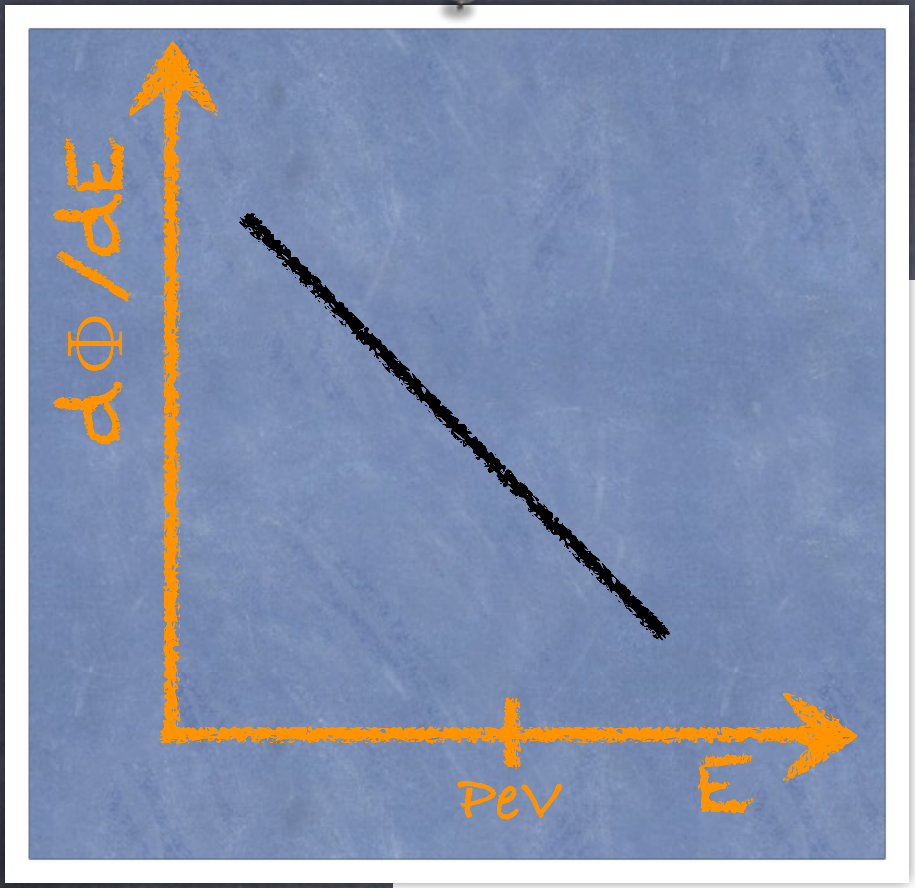


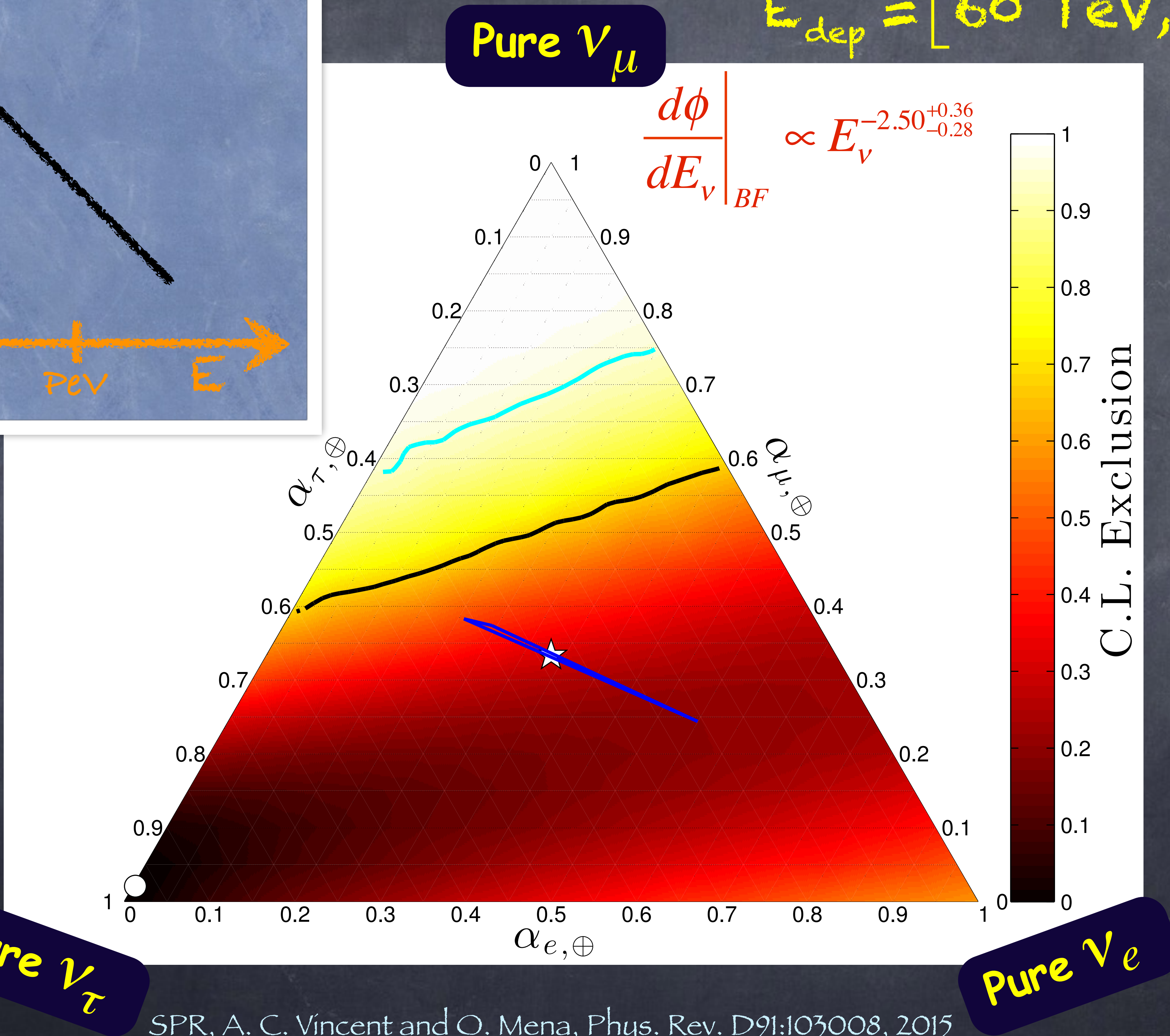


SPR, A. C. Vincent and O. Mena, Phys. Rev. D91:103008, 2015

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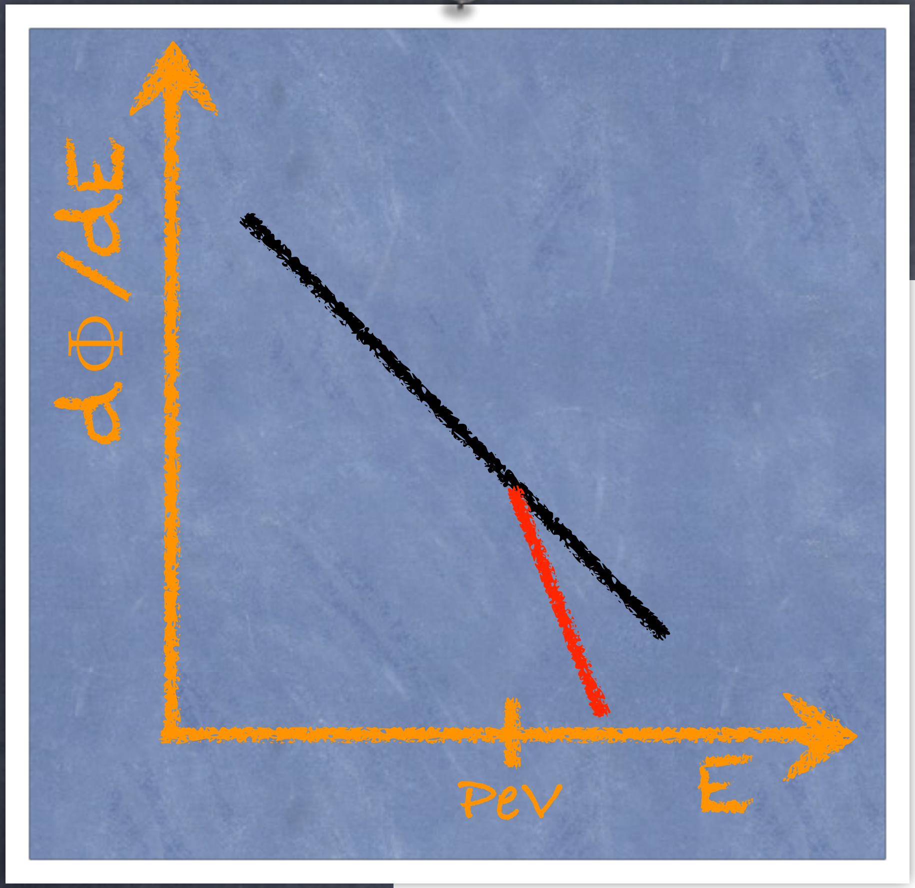
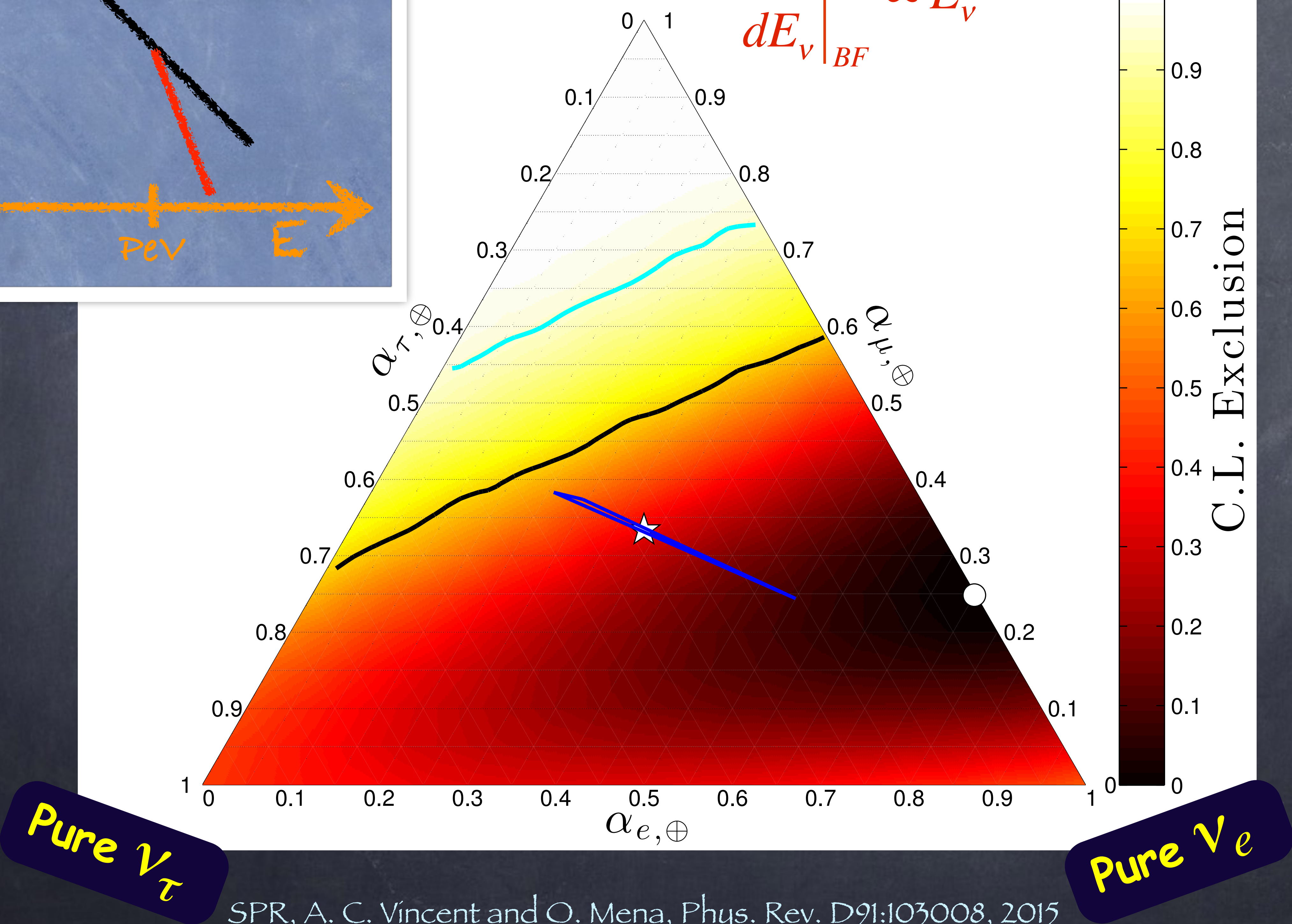
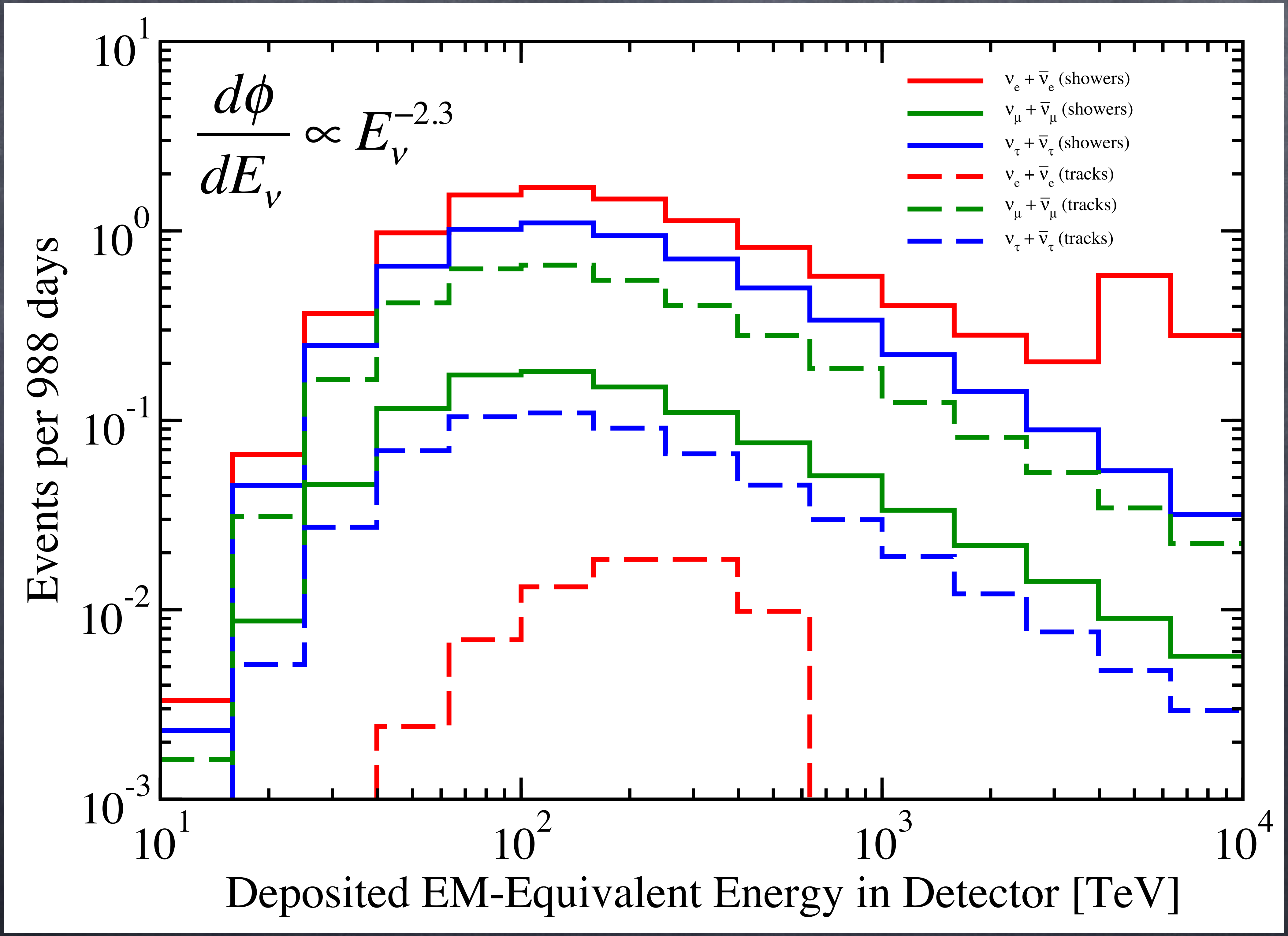



SPR, A. C. Vincent and O. Mena, Phys. Rev. D91:103008, 2015

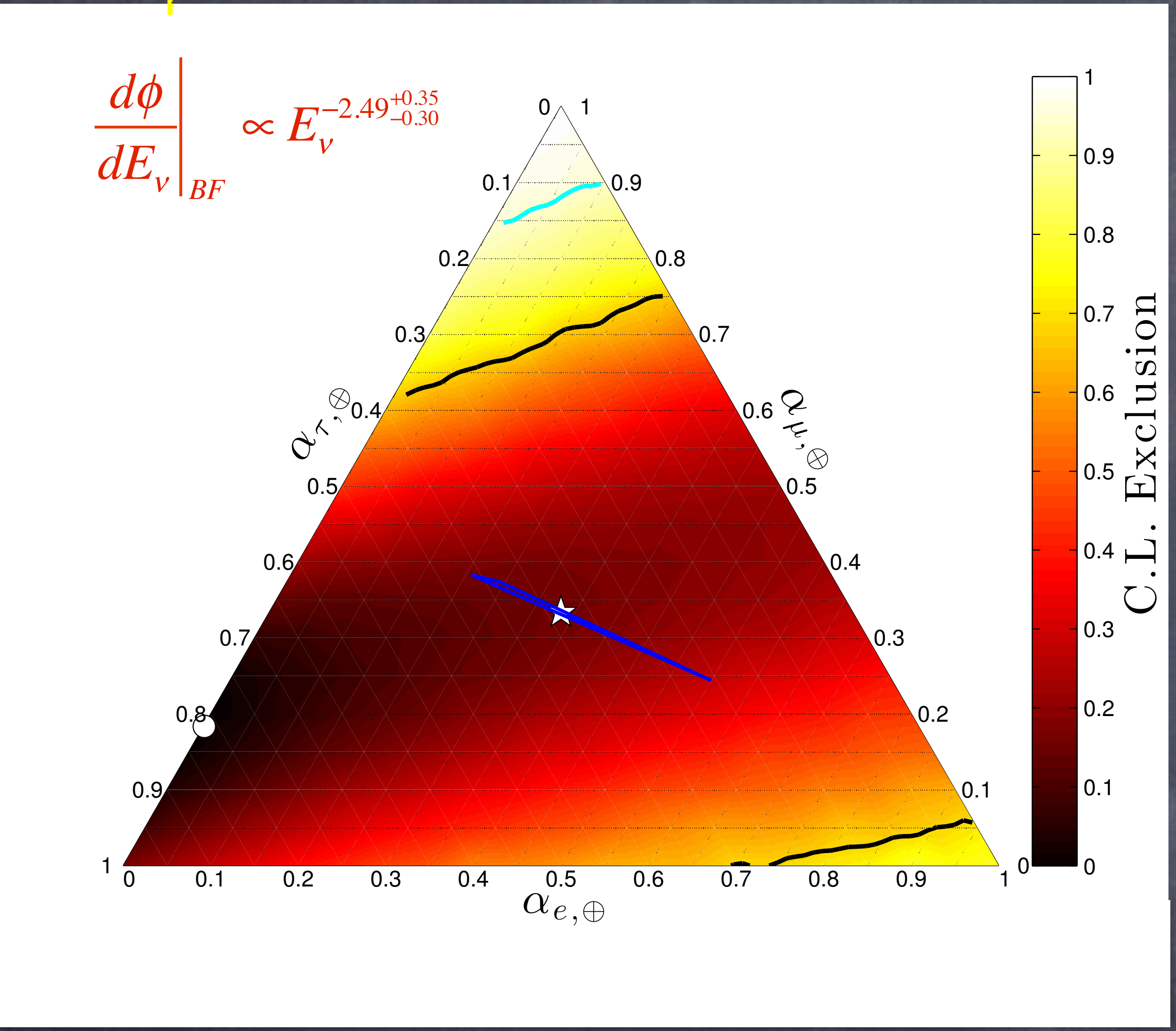
# Energy distribution of HESE




SPR, A. C. Vincent and O. Mena, Phys. Rev. D91:103008, 2015

# Effect of track misID

$E_{dep} = [60\ \text{TeV}, 10\ \text{PeV}]$




SPR, A. C. Vincent and O. Mena,
Phys. Rev. D91:103008, 2015

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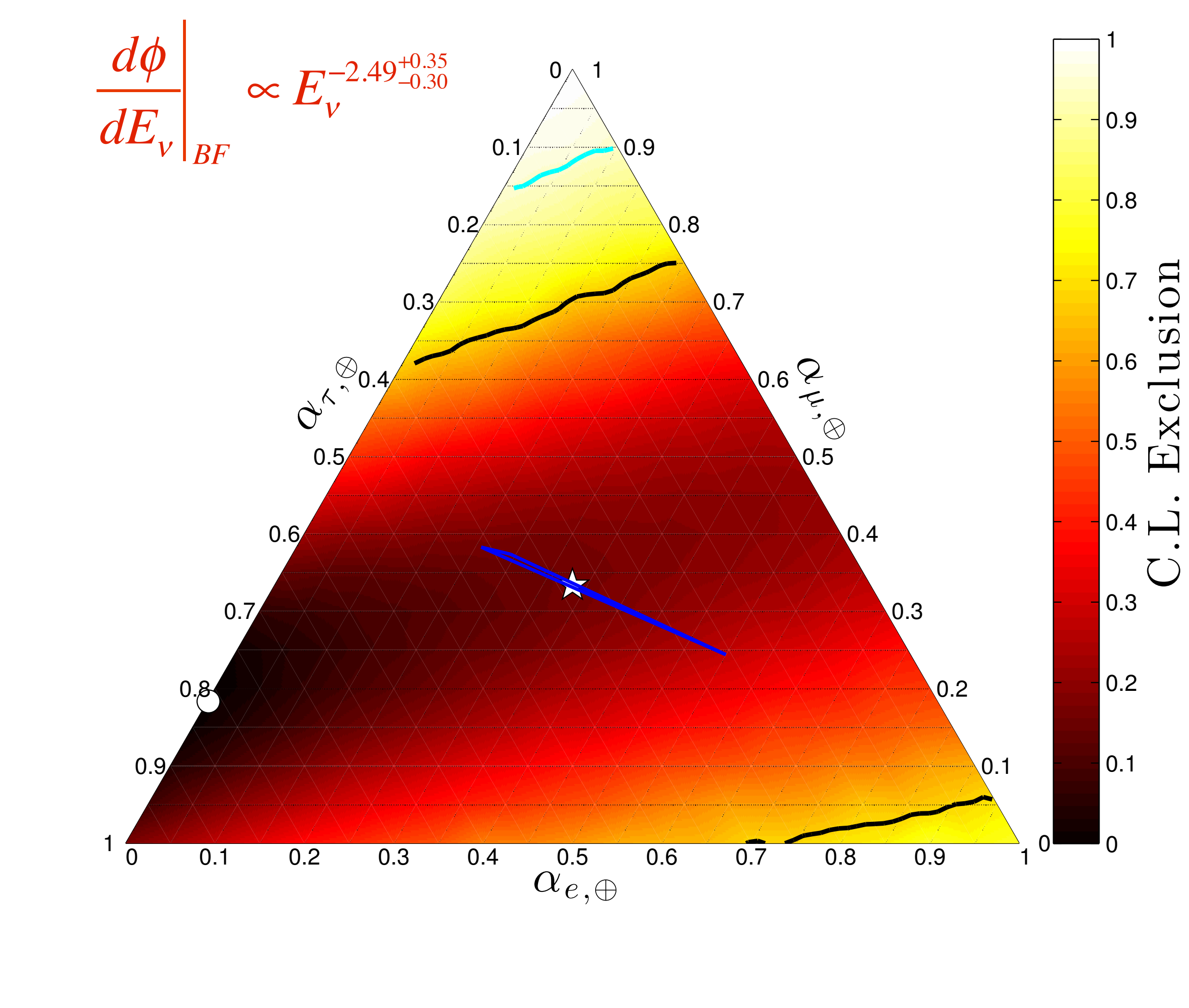
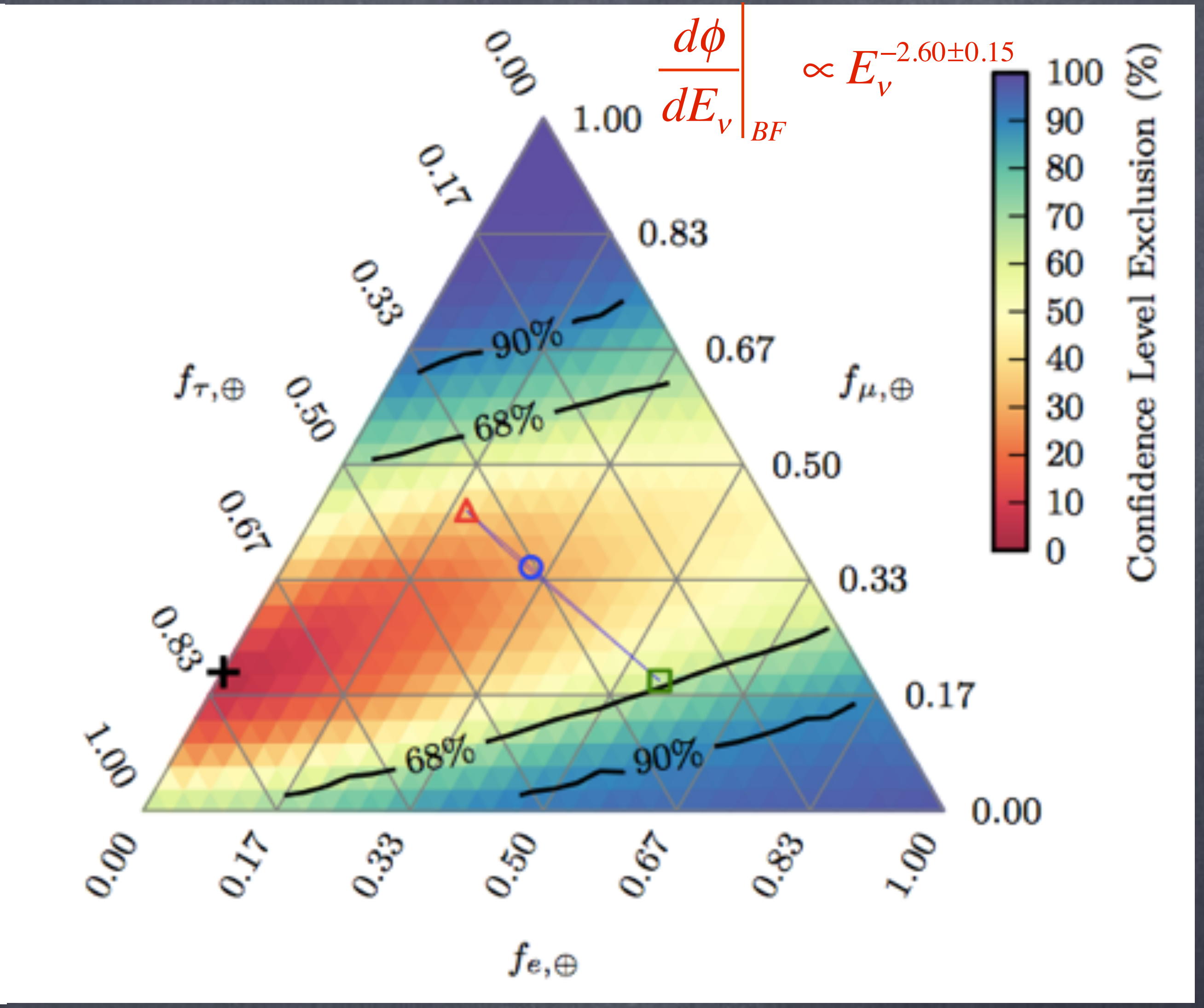
3-yr IceCube analysis




SPR, A. C. Vincent and O. Mena, Phys. Rev. D91:103008, 2015




M. G. Aartsen et al. [Icecube Collaboration], Phys. Rev. Lett. 114:171102, 2015

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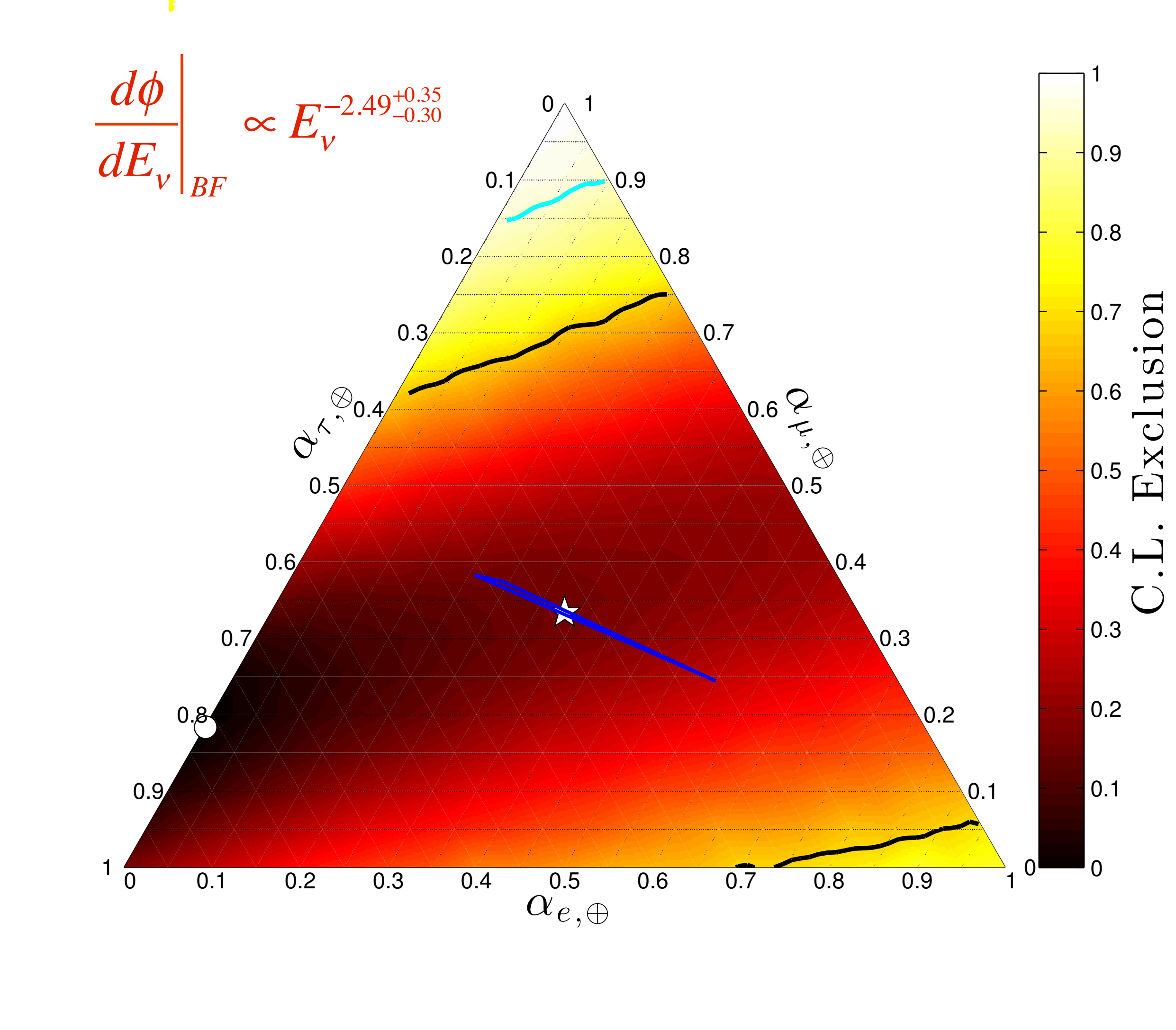
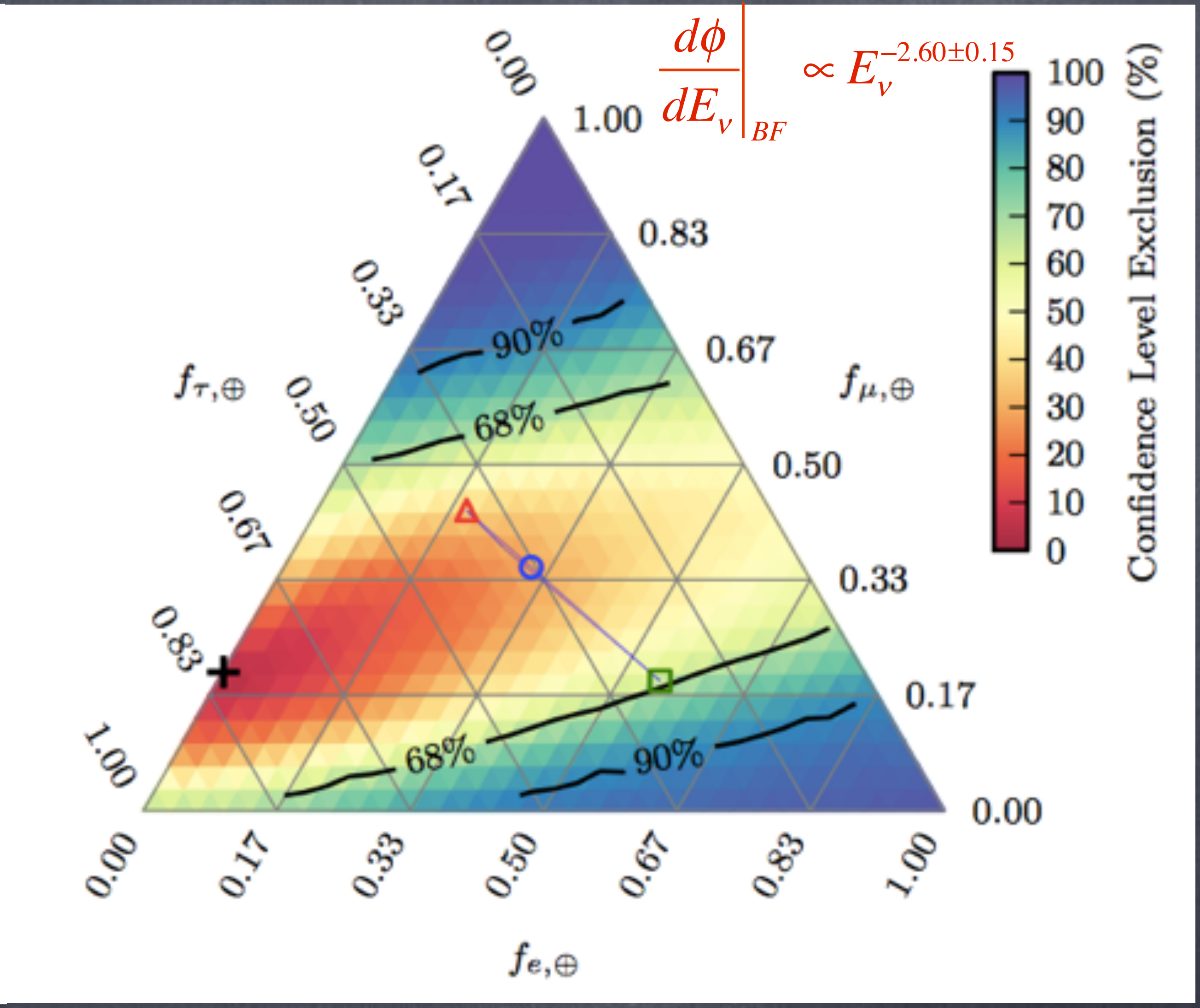


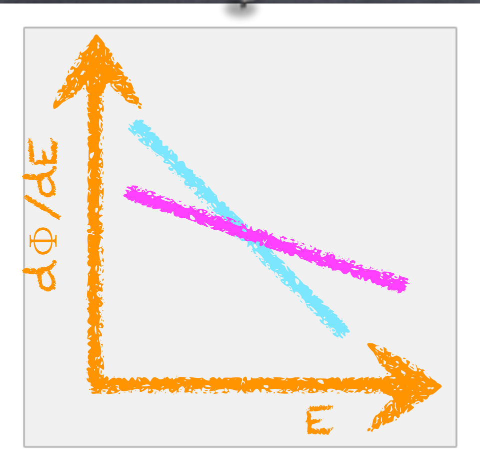

SPR, A. C. Vincent and O. Mena,
Phys. Rev. D91:103008, 2015

M. G. Aartsen et al.[Icecube Collaboration],
Phys. Rev. Lett. 114:171102, 2015

Differences between the IceCube analysis and
O. Mena, SPR and A. C. Vincent (PRL113:091103, 2014) are mainly due to
extending the deposited energy range to cover the Glashow resonance (+ track misID)

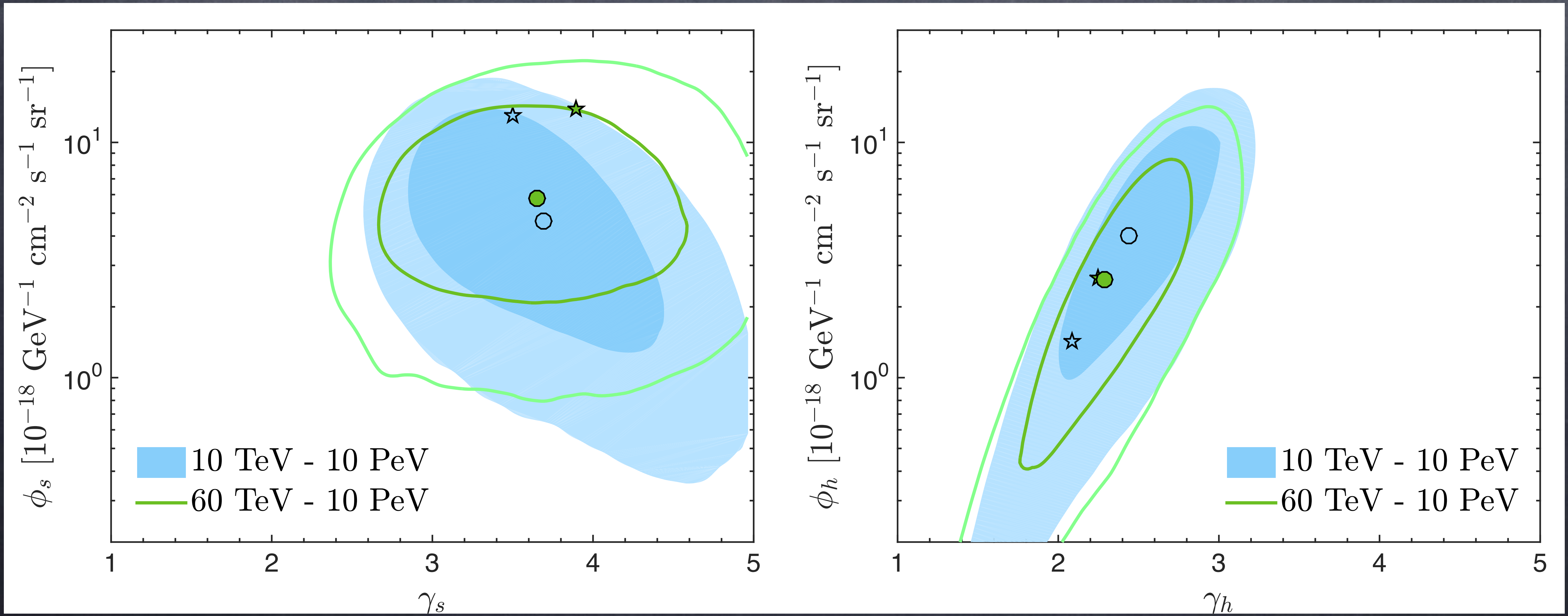
# Two power-law spectra

4-year data




Soft spectrum

Hard spectrum




A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# Two power-law spectra

4-year data

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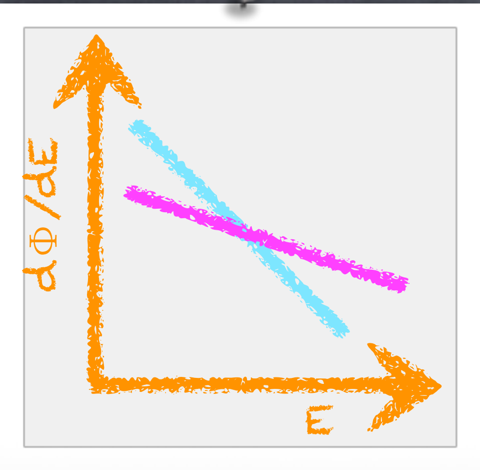
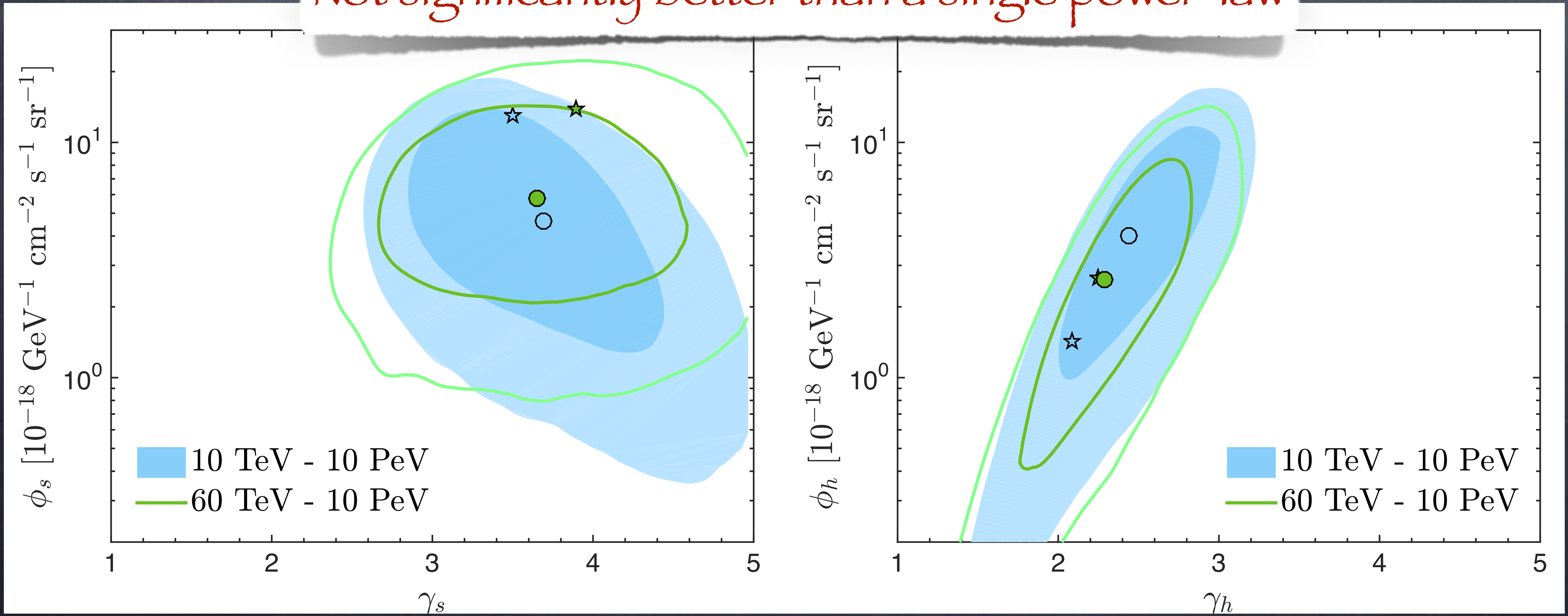



Hard spectrum

Not significantly better than a single power-law




A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

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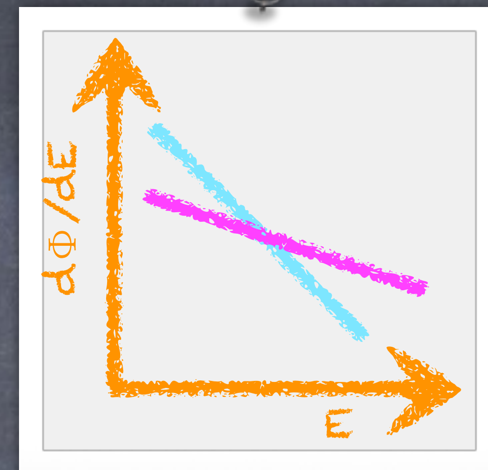
**4-year data**




**Soft spectrum**

**Hard spectrum**

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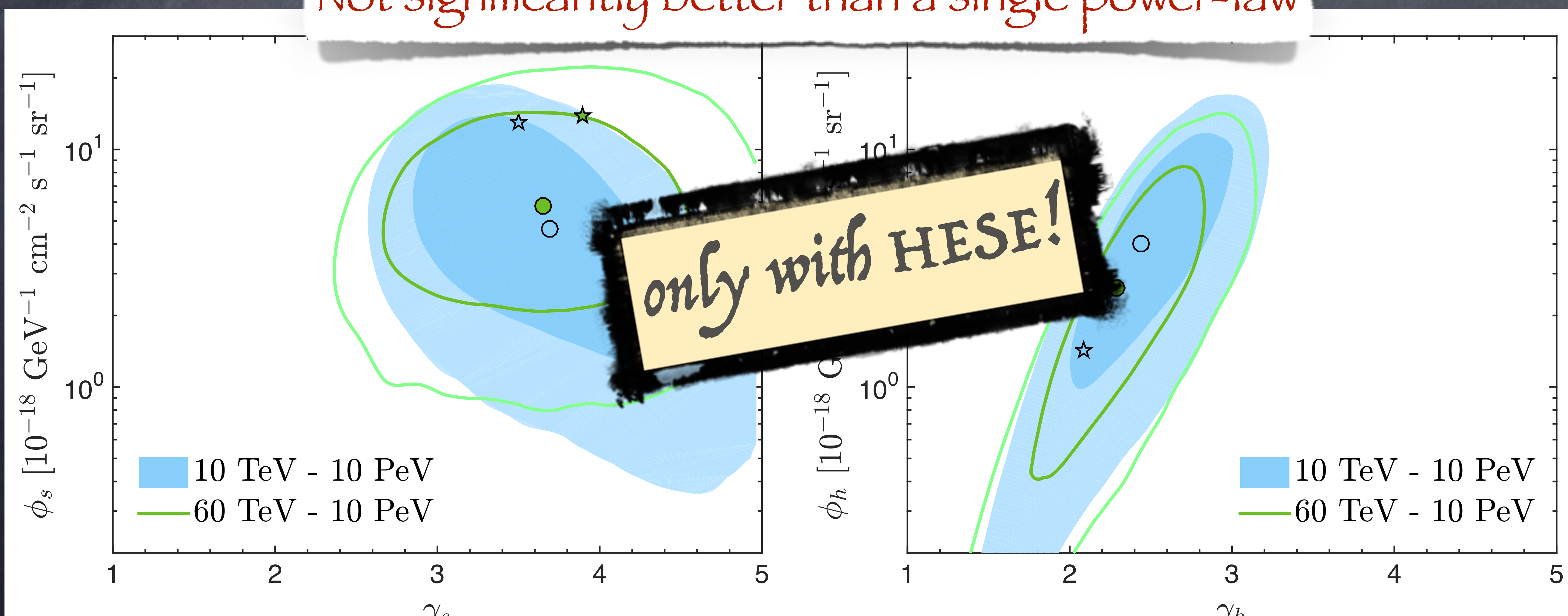


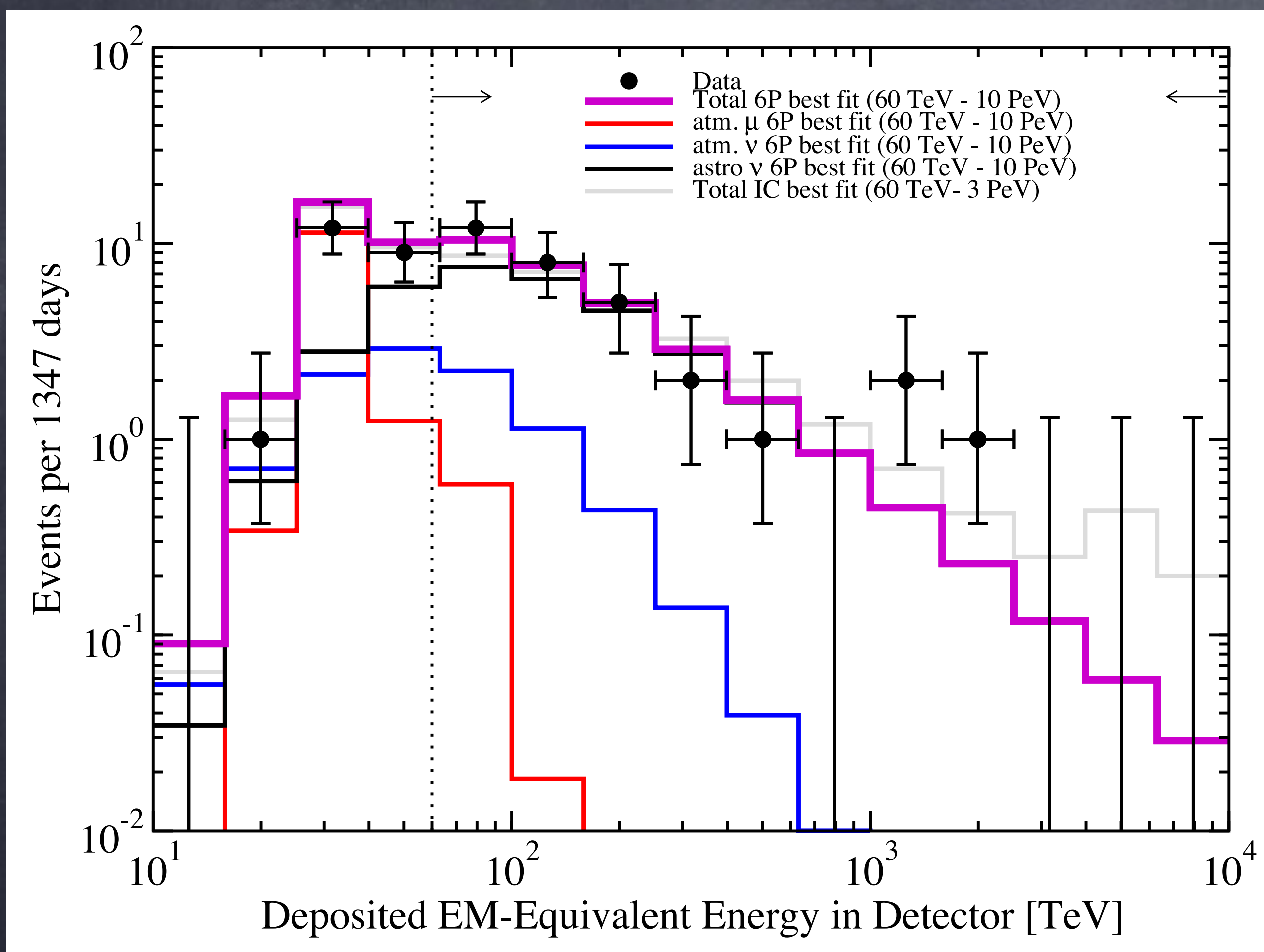

only with HESE!

A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# Event spectra

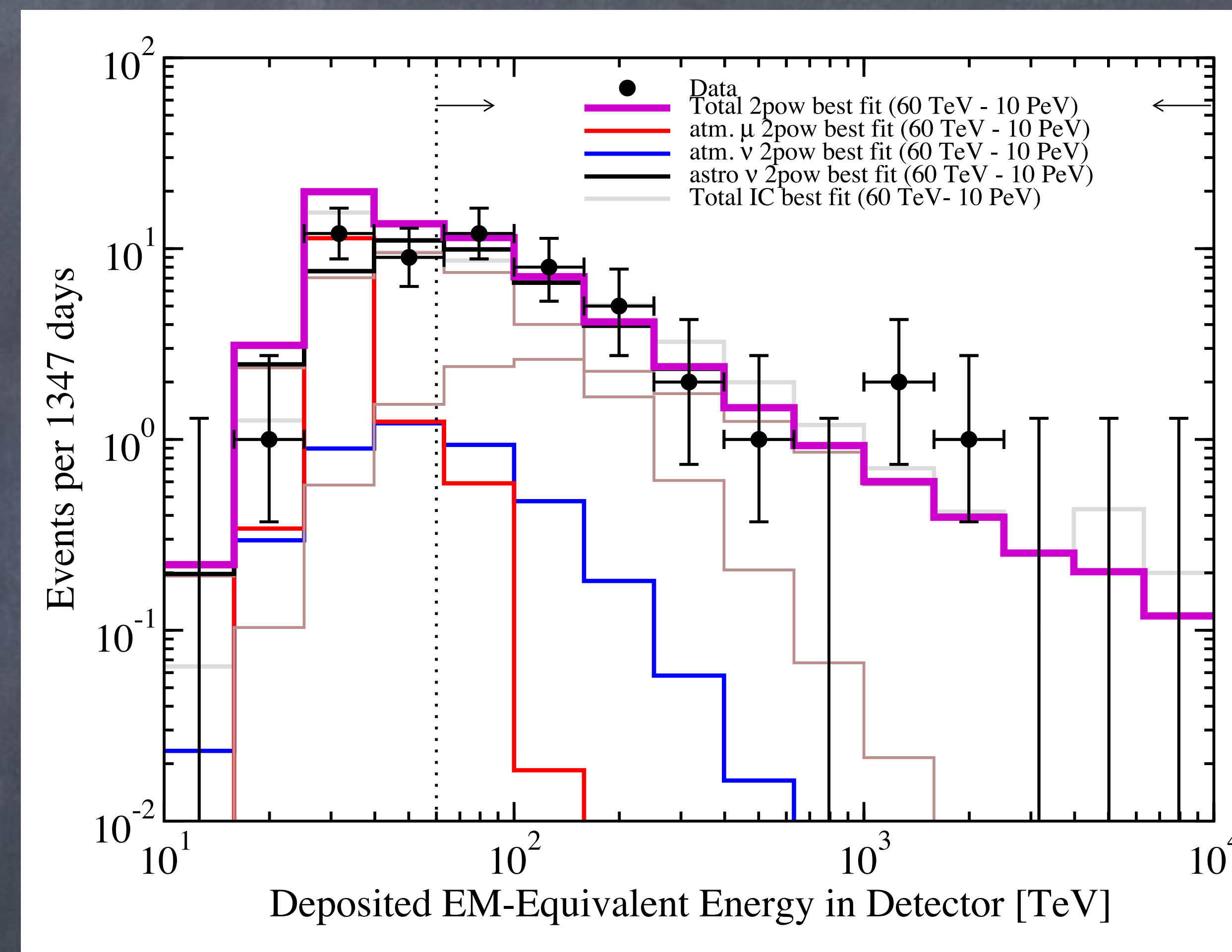
## 4-year data

### single power-law flux




$$E_\nu^2 \left.\frac{d\Phi}{dE_\nu}\right|_{BF} = 10.3 \left(\frac{E_\nu}{100\ \text{TeV}}\right)^{-0.77} \times 10^{-8}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

### two power-law flux




$$E_\nu^2 \left.\frac{d\Phi}{dE_\nu}\right|_{BF} = \left[13.8 \left(\frac{E_\nu}{100\ \text{TeV}}\right)^{-1.89} + 2.7 \left(\frac{E_\nu}{100\ \text{TeV}}\right)^{-0.25}\right] \times 10^{-8}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

IC best fit [60 TeV - 3 PeV]
(1:1:1)

$$E_\nu^2 \left.\frac{d\Phi}{dE_\nu}\right|_{BF} = 6.6 \left(\frac{E_\nu}{100\ \text{TeV}}\right)^{-0.58} \times 10^{-8}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

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## 4-year data

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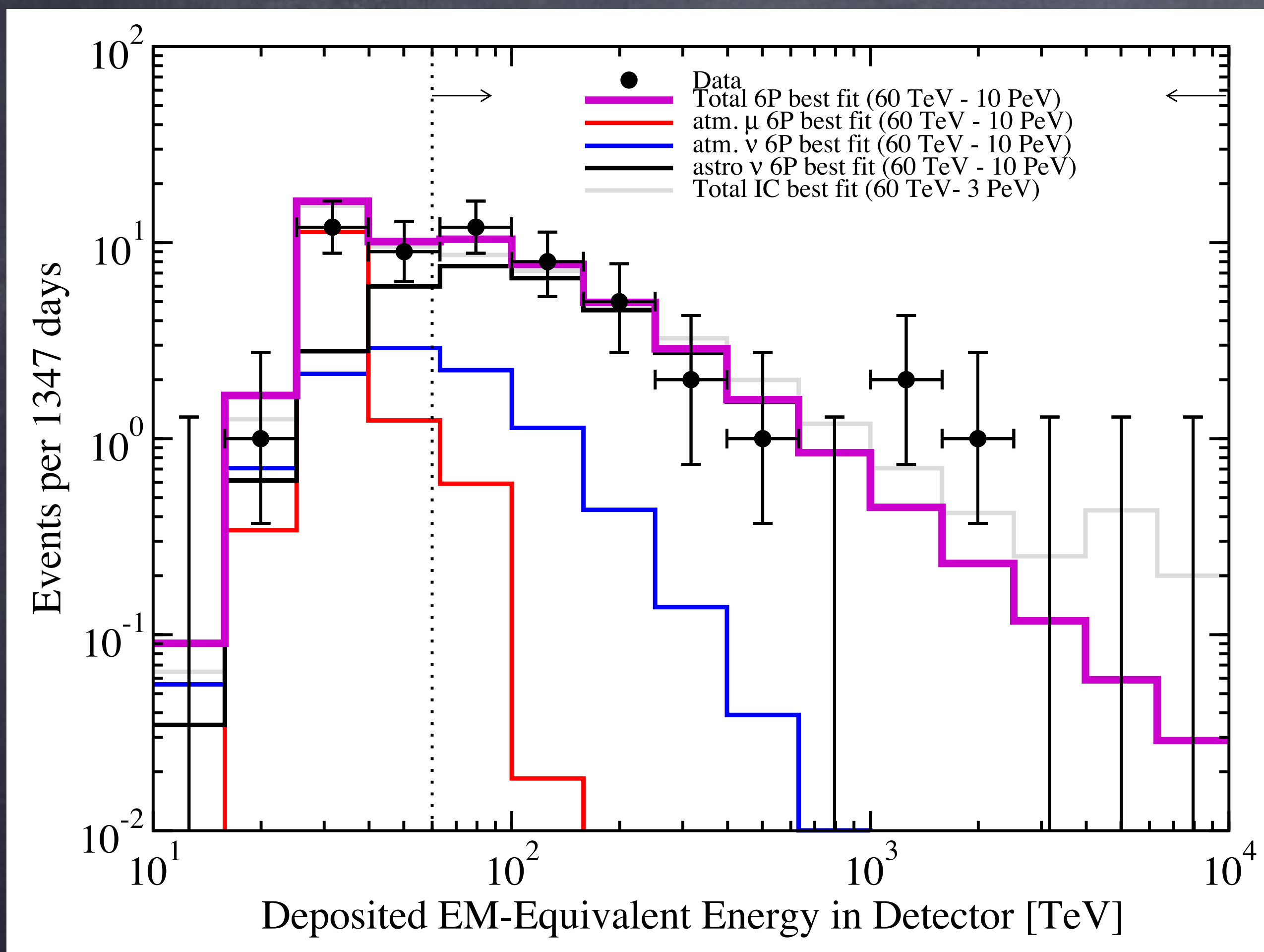


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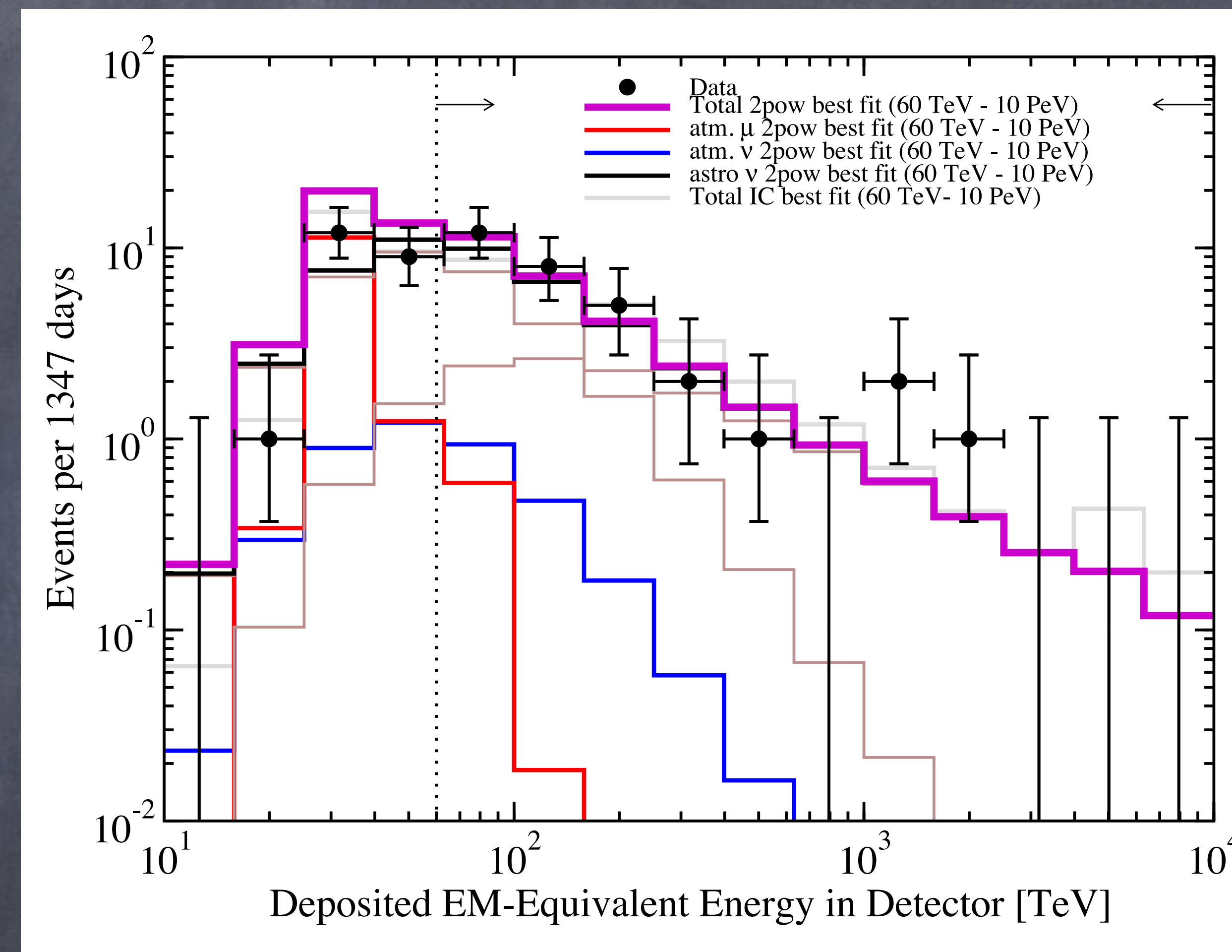


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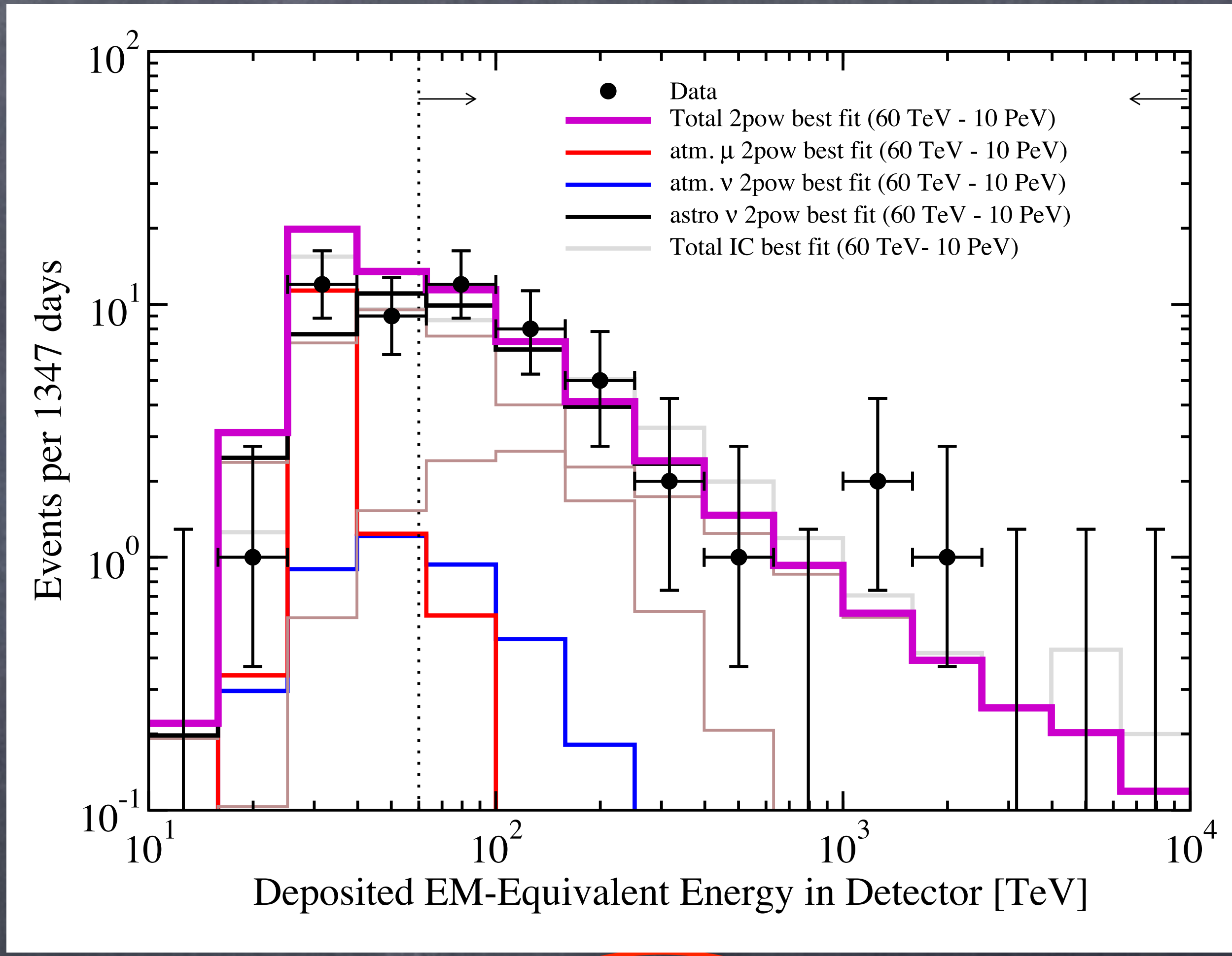
consistent with the through-going muons best fit

A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# Event spectra

## 4-year data

## Two power-law flux

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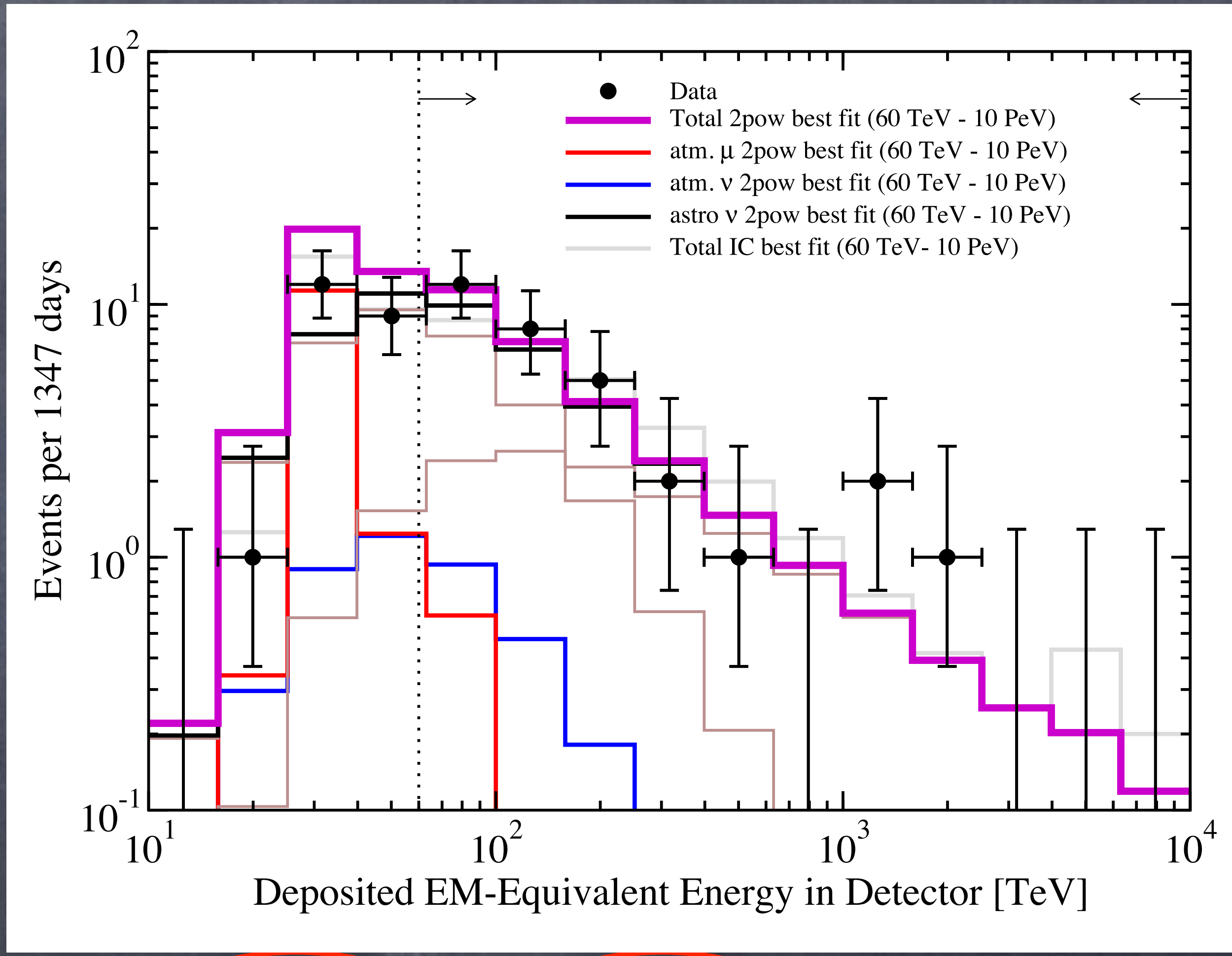
Adapted from: A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# Event spectra

4-year data

two power-law flux

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very soft

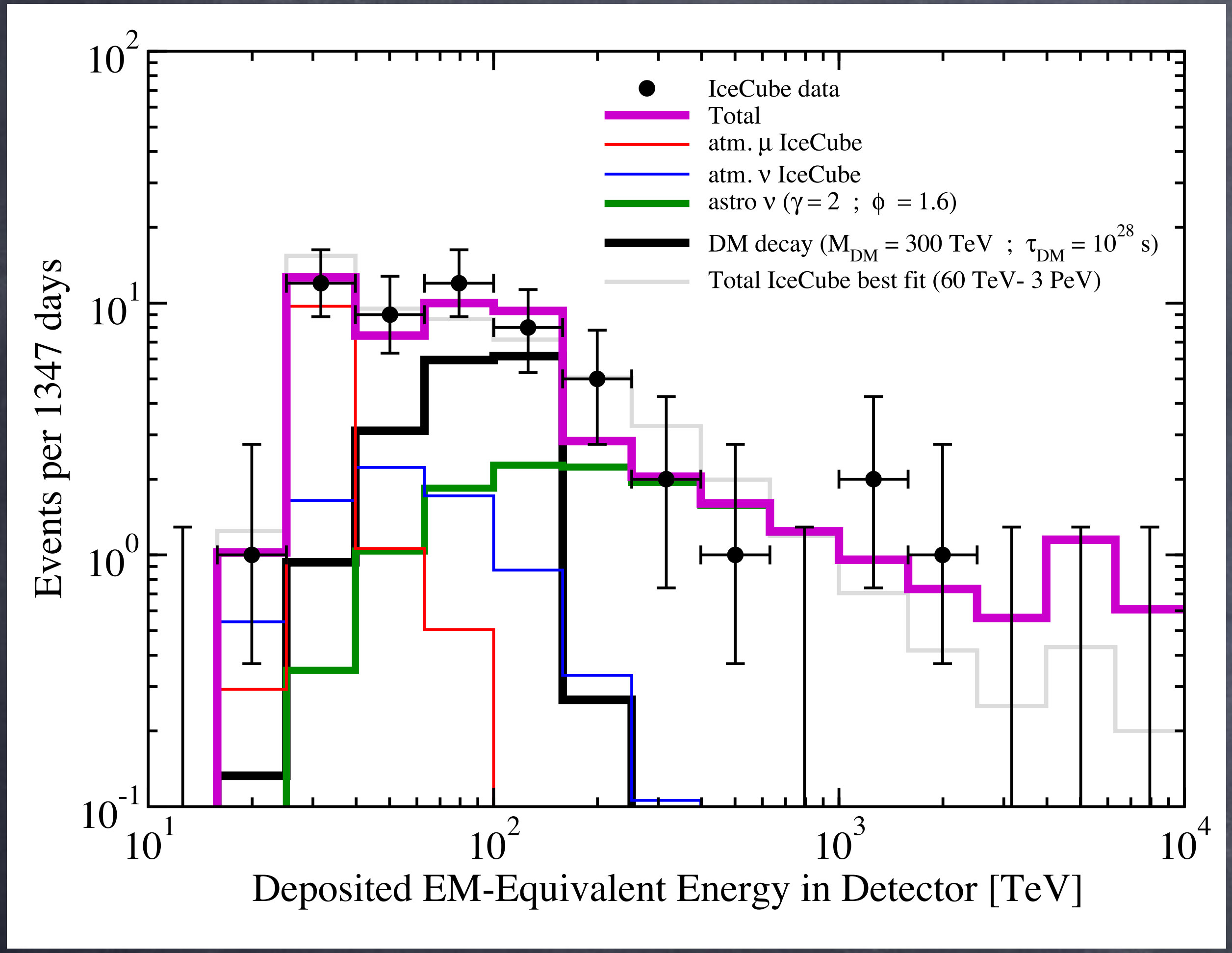
consistent with the through-going muons best fit

Adapted from: A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# Event spectra

## 4-year data

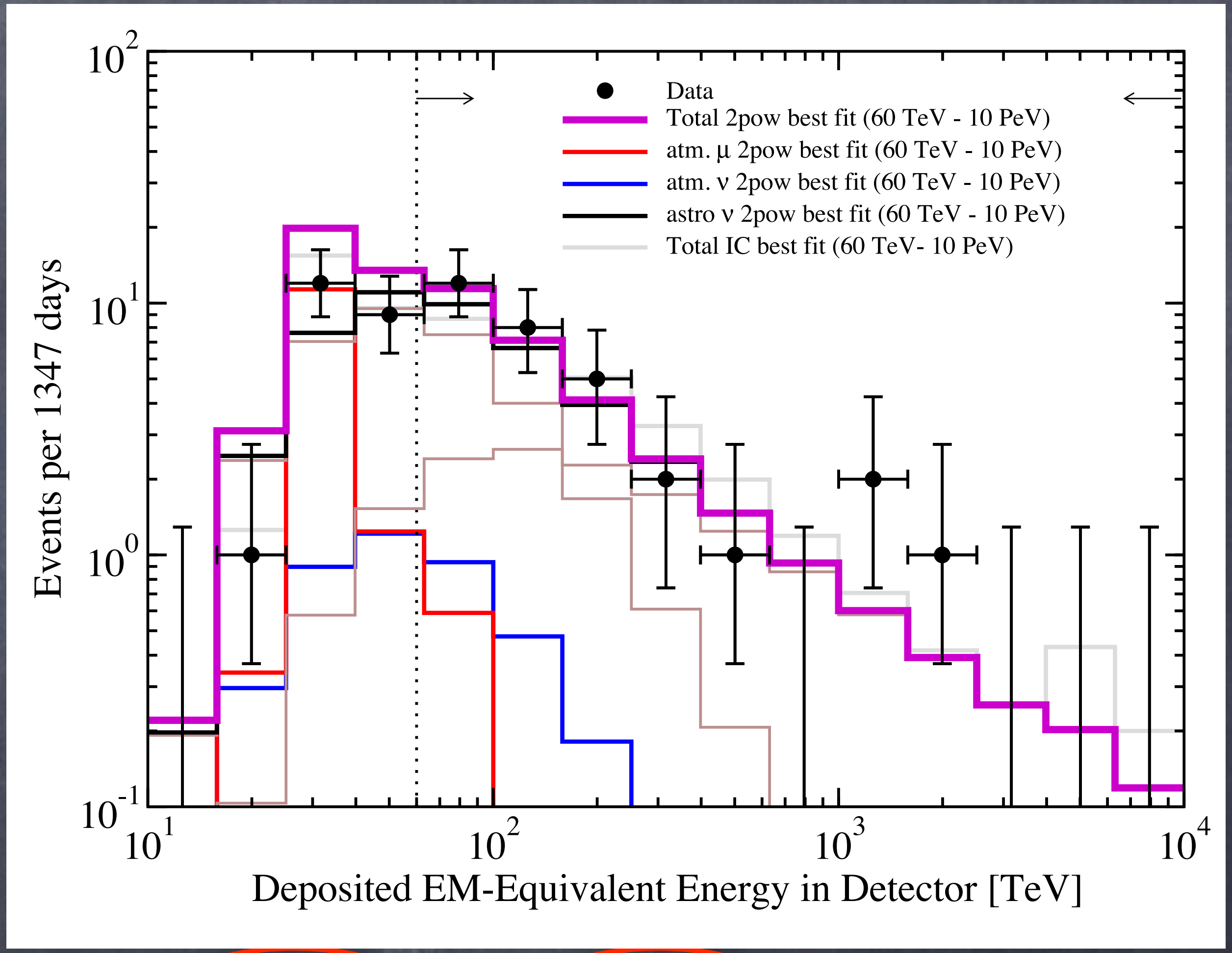
### power-law flux + DM decay




$$E_\nu^2 \frac{d\Phi}{dE_\nu}\Big|_{BF} = 1.6\times 10^{-8}\ \mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}} + \text{DM decay}$$

P. Di Bari, P. O. Ludl and SPR, JCAP 1611:044, 2016

### two power-law flux

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very soft

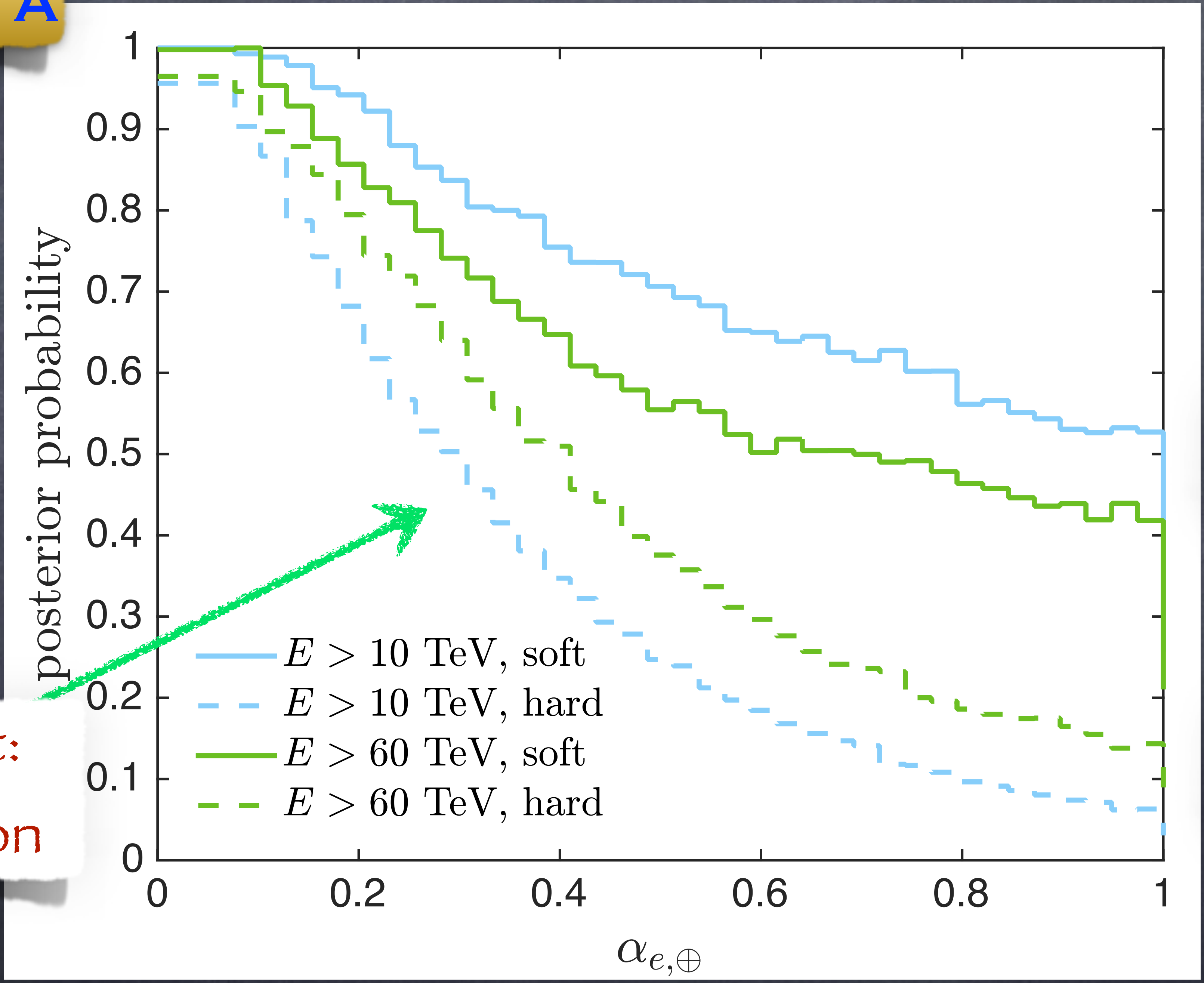
consistent with the through-going muons best fit

Adapted from: A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# Two power-law Flavor

Assuming equal flavor fractions for $\nu_\mu$ and $\nu_\tau$

4-year data




Soft component

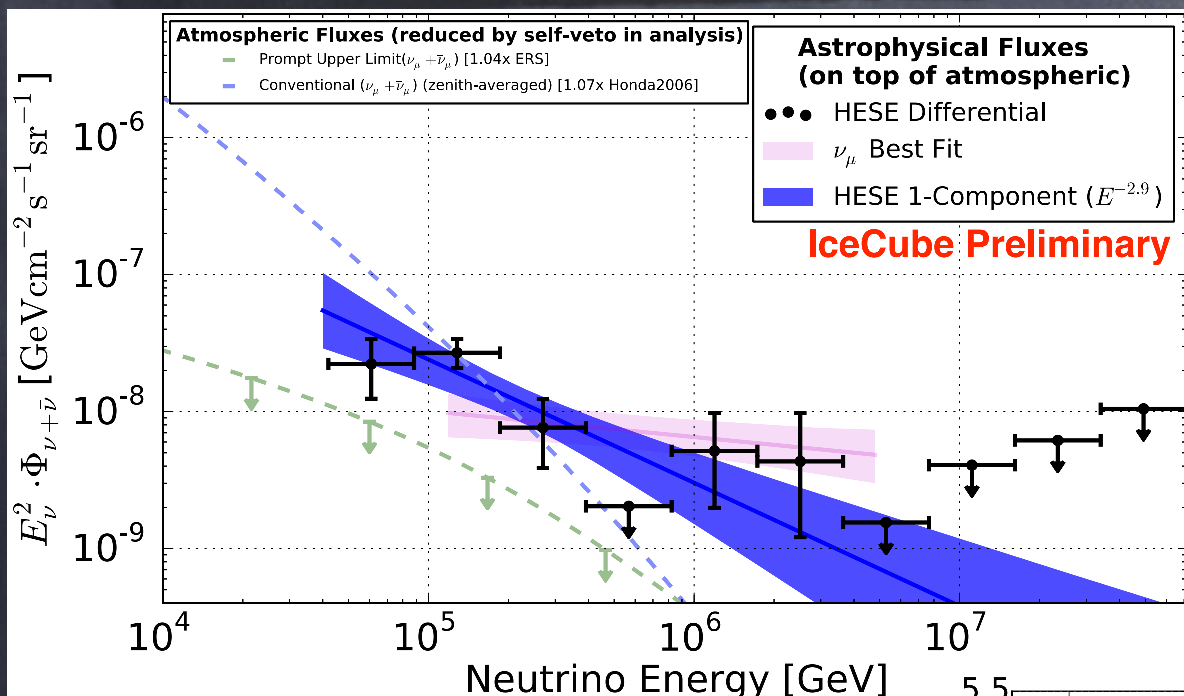
Hard component

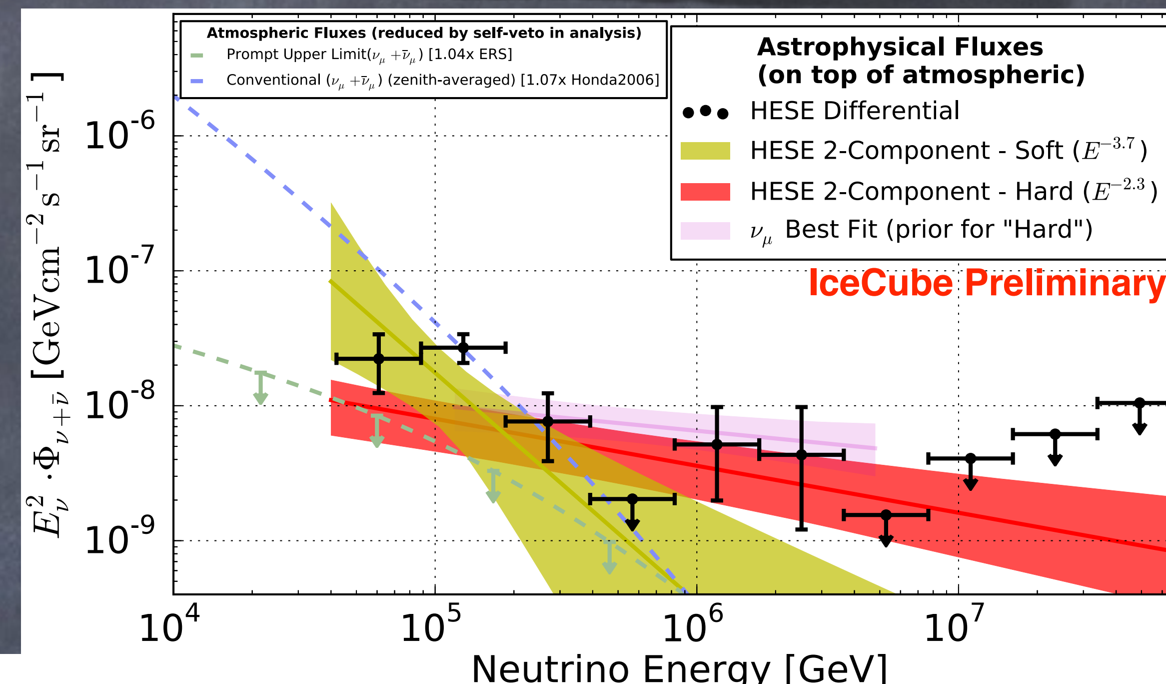
Hard component: larger $\nu_\mu$ fraction

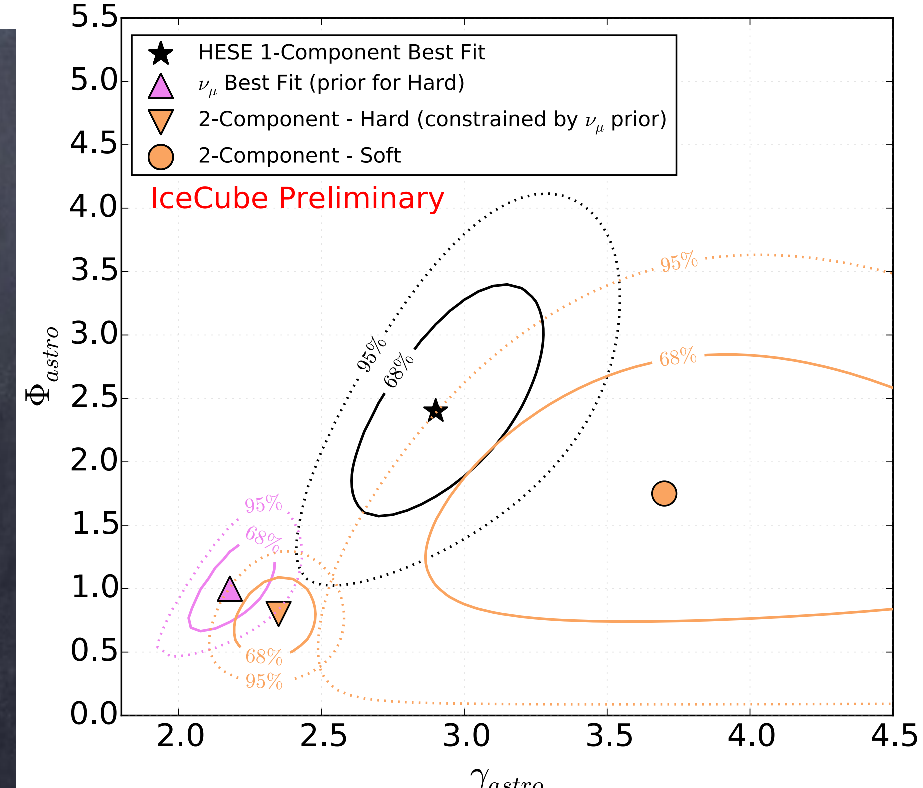
A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# Recent 6-yr HESE

Two power-law spectrum is just a bit better than a single power-law




C. Kopper [IceCube Collaboration], PoS (ICRC2017) 981

# Other inputs that could affect current analyses

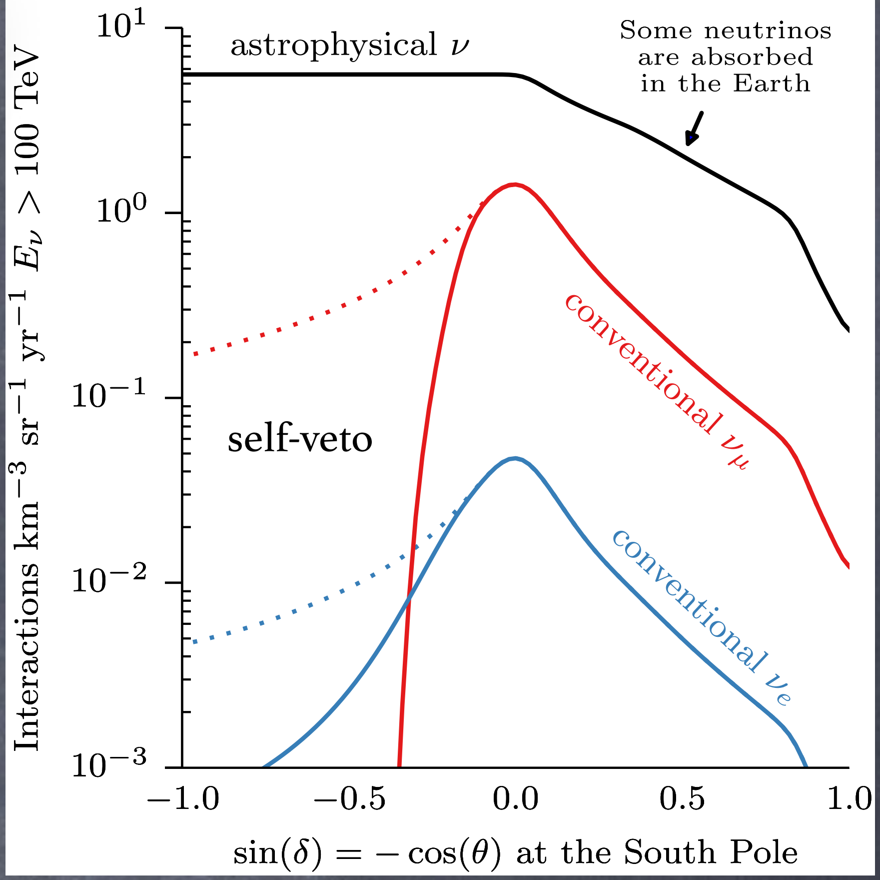
J. van Santen ICRC2017

*atmospheric neutrino self-veto uncertainties*

Using SIBYLL 2.1 and DPMJET 2.55

S. Schönert, T. Gaisser, E. Resconi and O. Schulz, Phys. Rev. D79:043009, 2009

T. Gaisser, K. Jero, A. Karle, J. Van Santen, Phys. Rev. D90:023009, 2014



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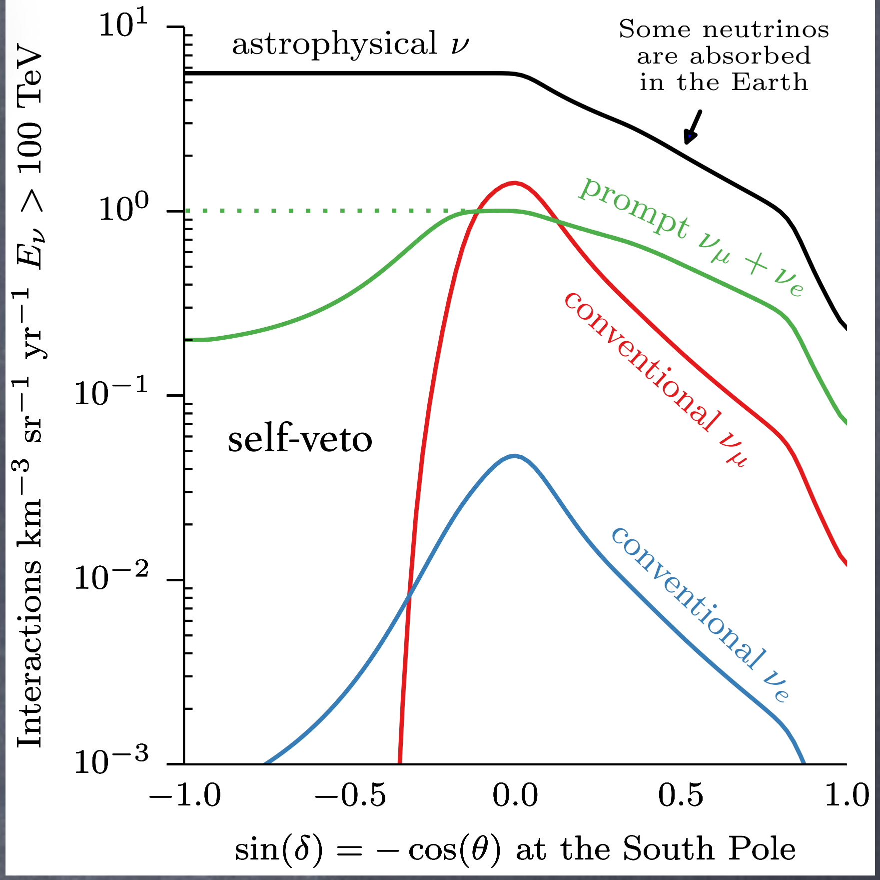

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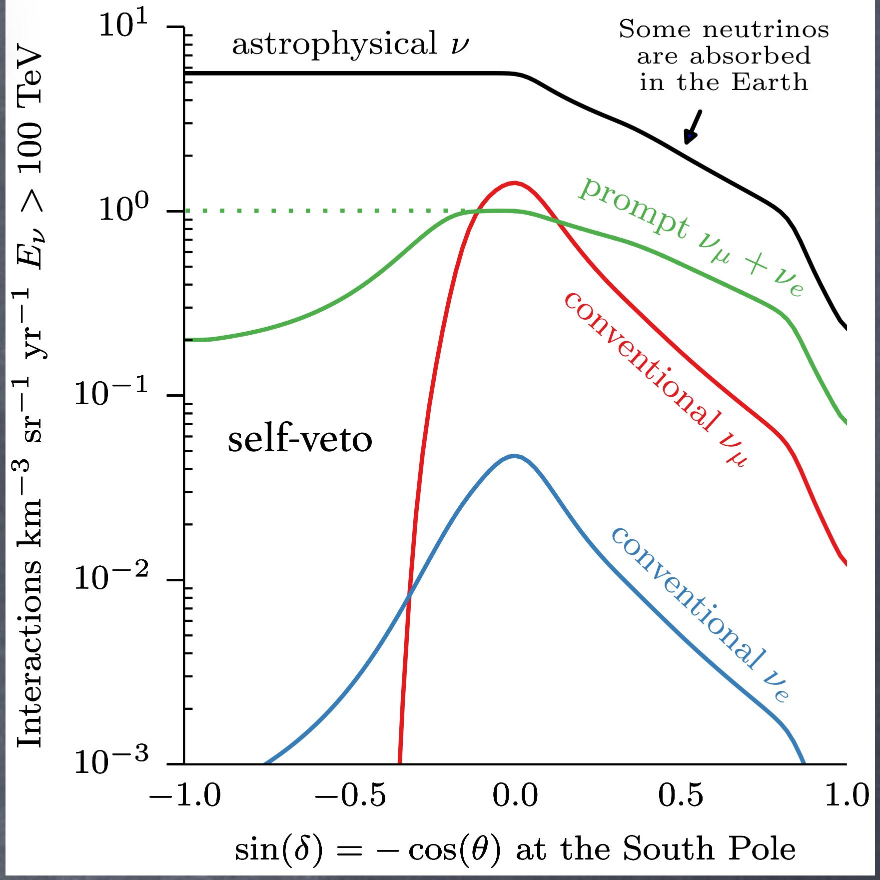
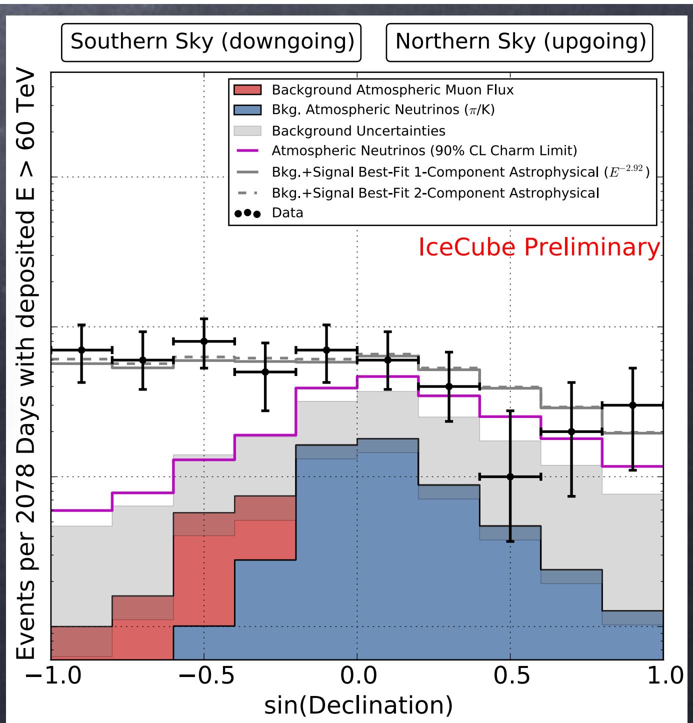



incompatible with prompt neutrinos

C. Kopper, ICRC2017

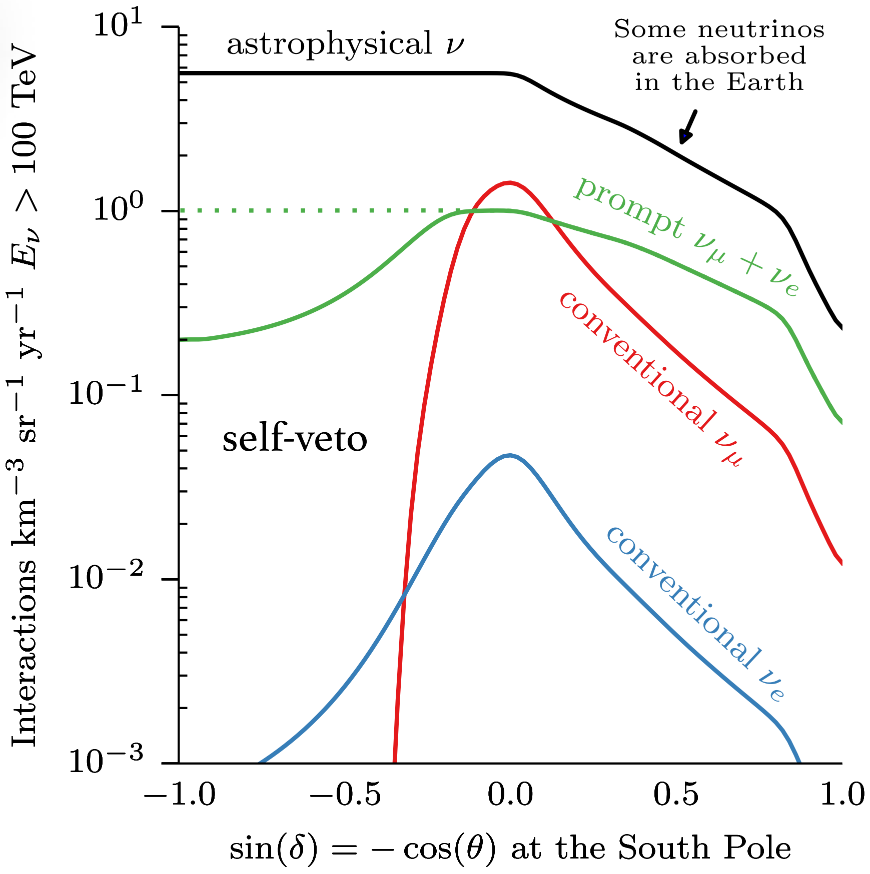
# Other inputs that could affect current analyses

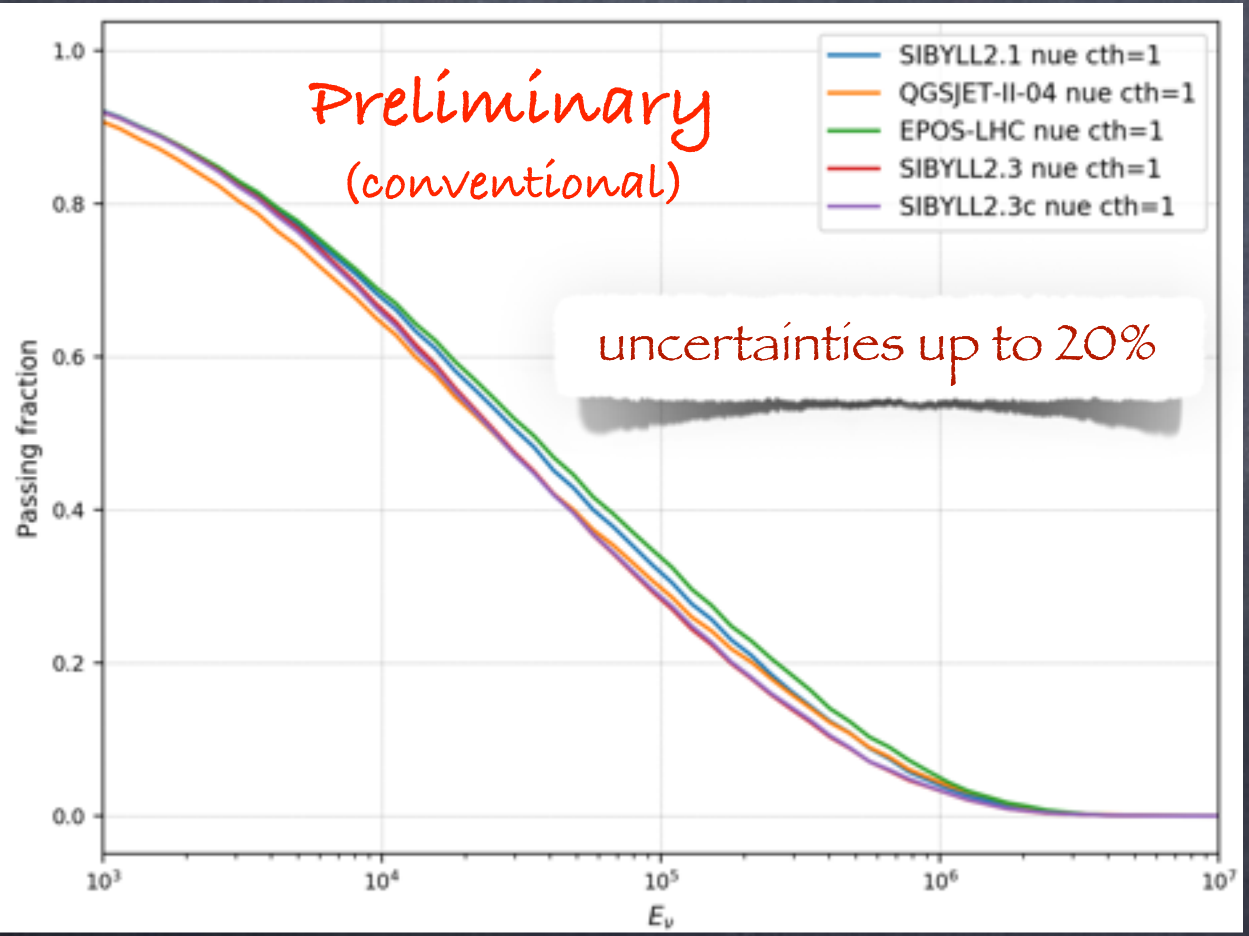
J. van Santen ICRC2017

*atmospheric neutrino self-veto uncertainties*

Using SIBYLL 2.1 and DPMJET 2.55

S. Schönert, T. Gaisser, E. Resconi and O. Schulz, Phys. Rev. D79:043009, 2009
T. Gaisser, K. Jero, A. Karle, J. Van Santen, Phys. Rev. D90:023009, 2014



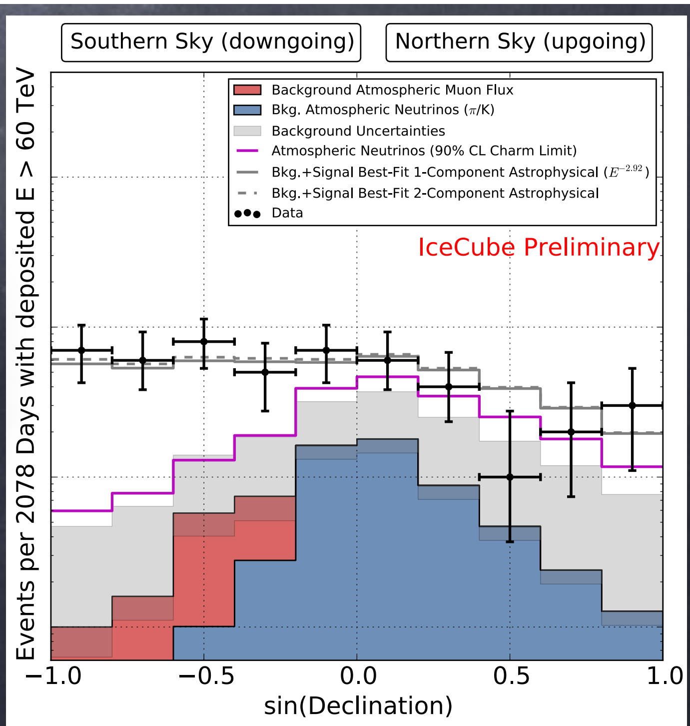




Preliminary (conventional)

uncertainties up to 20%

C. Argüelles, SPR, A. Schneider, L. Willie and T. Yuan, in preparation

incompatible with prompt neutrinos




C. Kopper, ICRC2017

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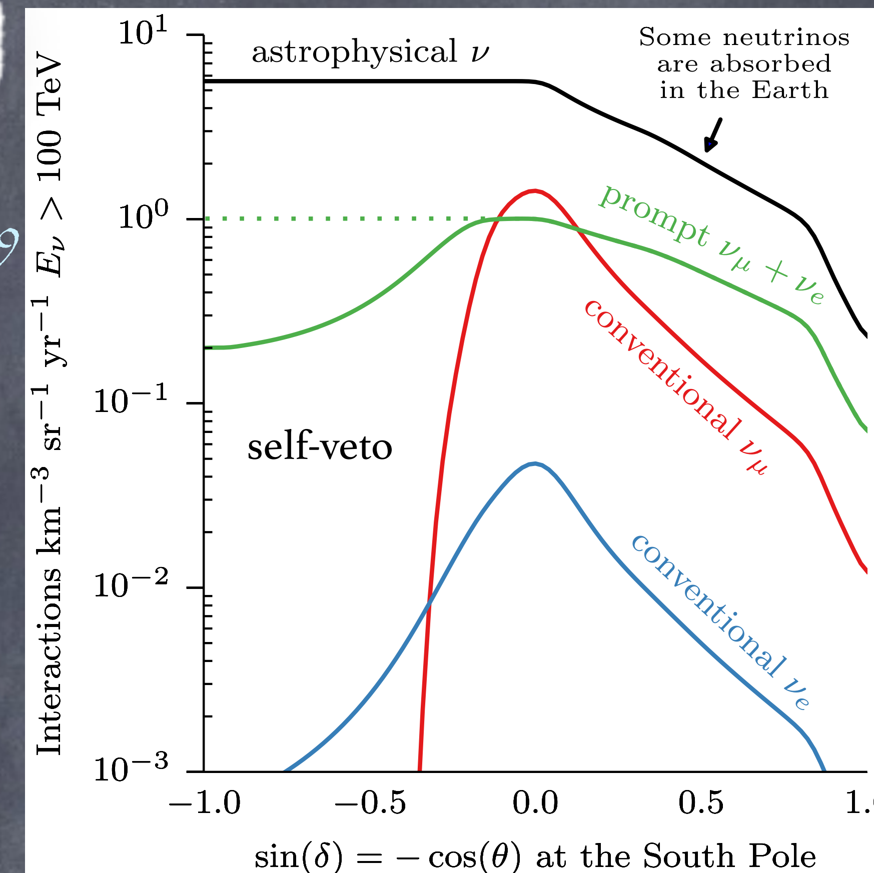
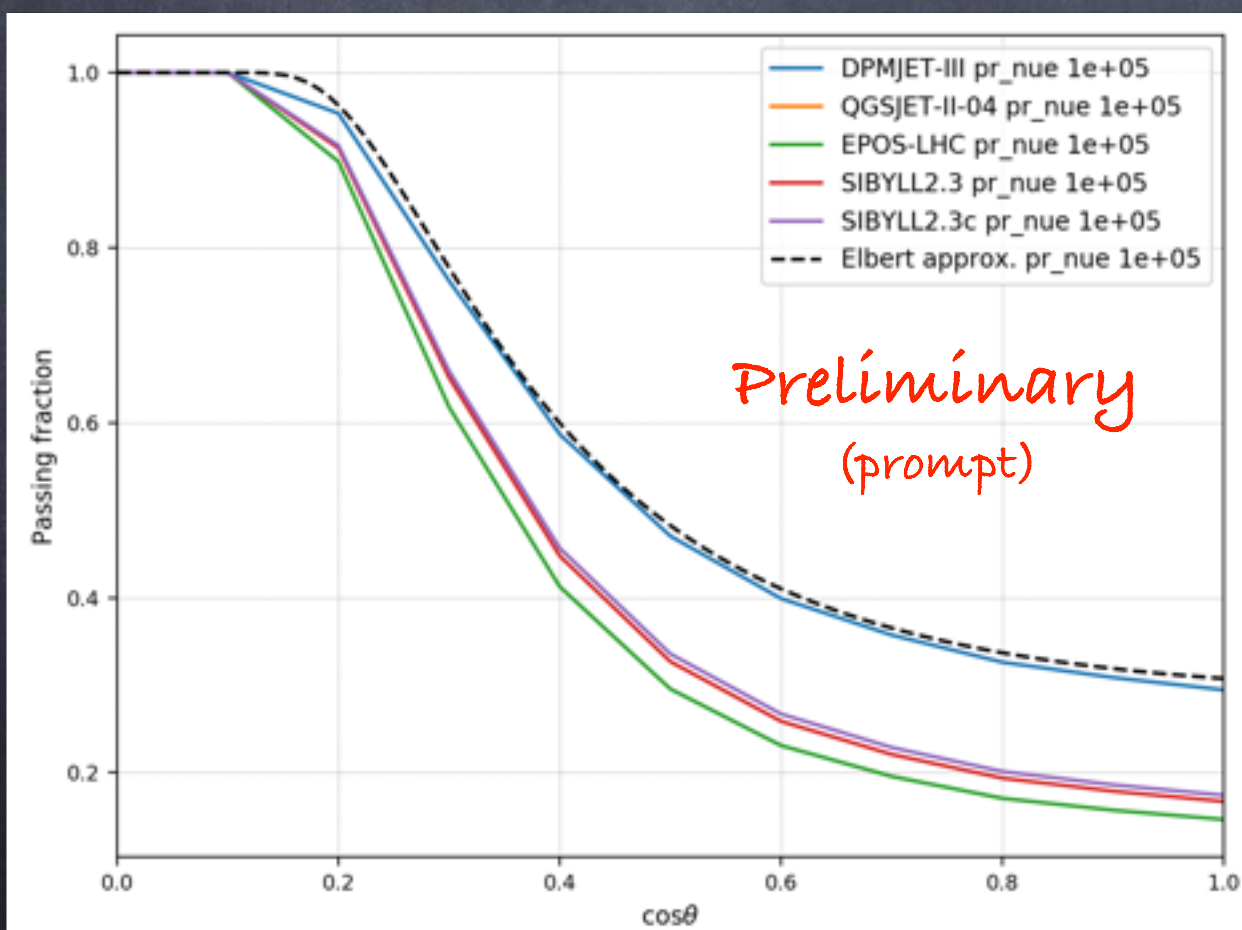
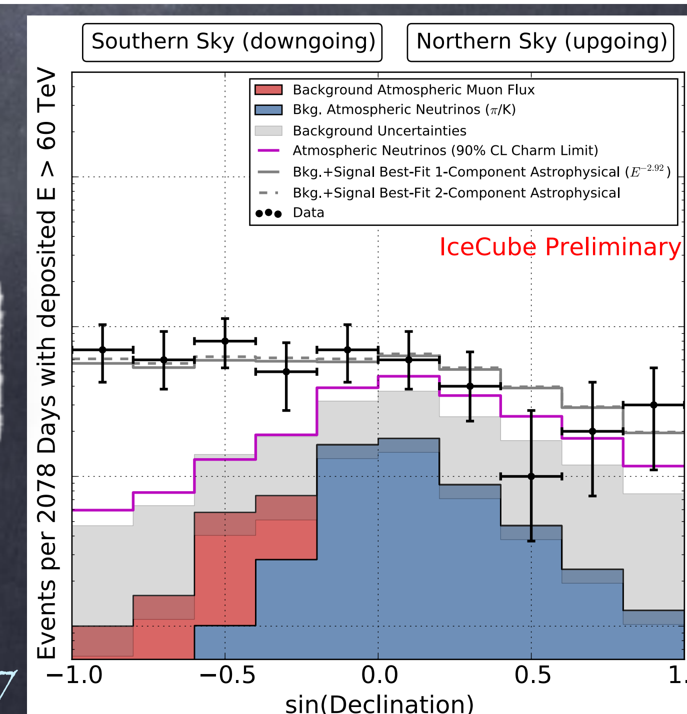



incompatible with prompt neutrinos




C. Argüelles, SPR, A. Schneider, L. Willie and T. Yuan, in preparation

C. Kopper, ICRC2017

# Other inputs that could affect current analyses

## track mis-ID parameterization

So far only provided as a constant fraction: 30% for HESE

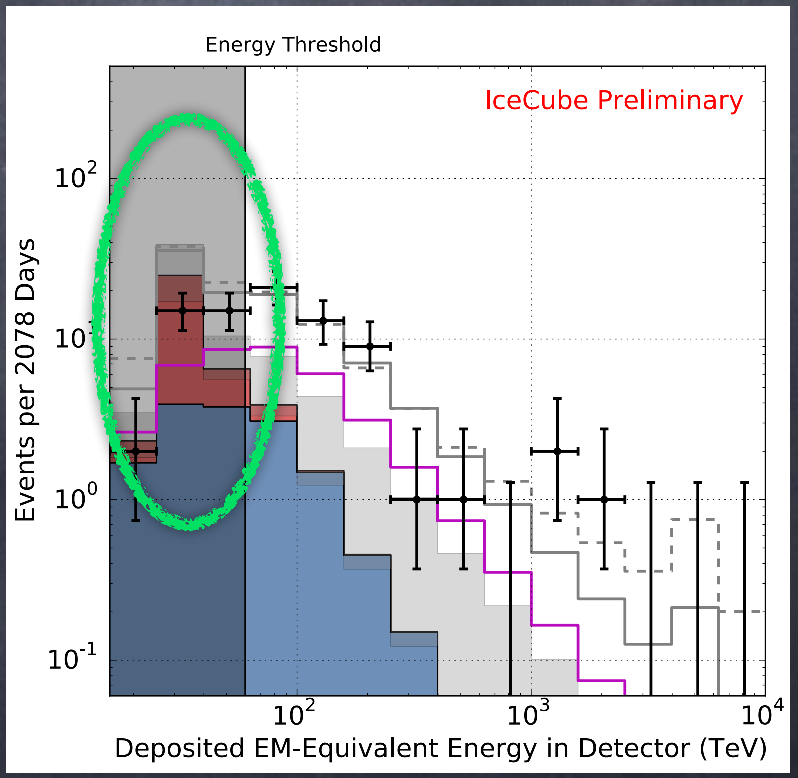
M. G. Aartsen et al. [Icecube Collaboration], Phys. Rev. Lett. 114:171102, 2015

it must be energy-dependent: it affects energy distributions

SPR, A. Vincent and O. Mena, in preparation

## atmospheric muon background

too large normalization as compared to observed events

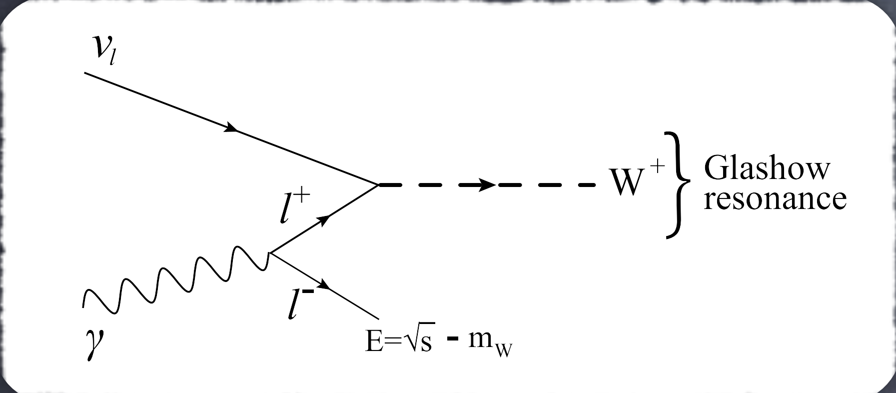


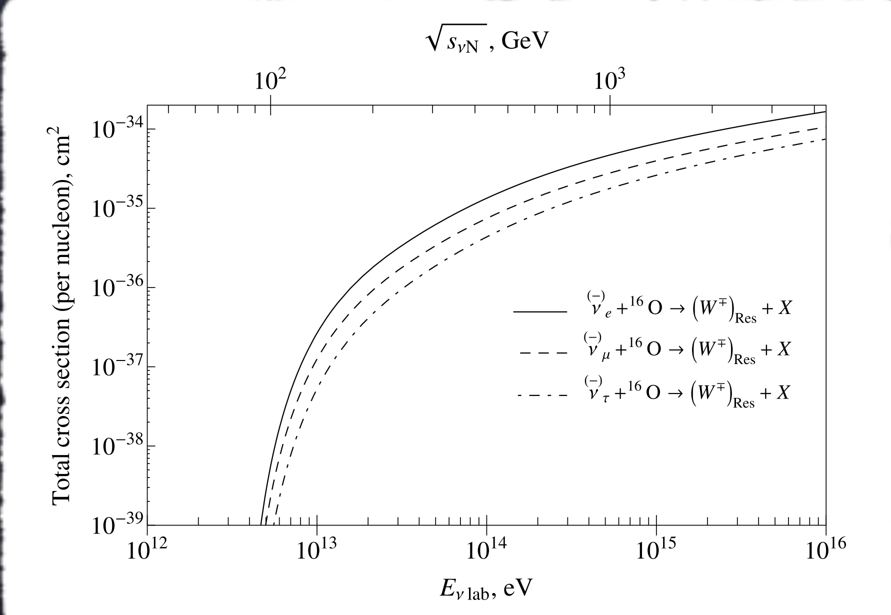

C. Kopper [IceCube Collaboration], PoS (ICRC2017) 981

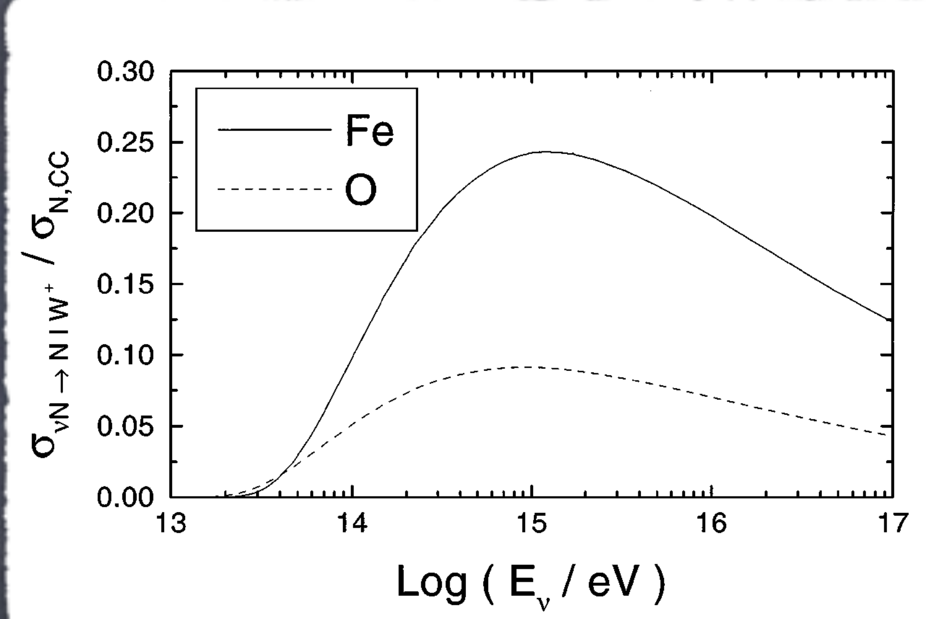
# Other inputs that could affect current analyses

**extra SM contribution: Hidden Glashow resonance**

D. Seckel, Phys. Rev, Lett. 80:900, 1998
I. Alikhanov, Phys. Lett. 741:295, 2015;
Phys. Lett. 756:247, 2016




up to 10% effect in detection
>10% effect in absorption in the Earth
effect in the energy and flavor distributions

C. Argüelles, SPR and M. H. Reno, in preparation

# Conclusions

- Flavor triangle is important for searches of exotic physics: degeneracies with energy spectrum

- Potential issues in current data (assuming an unbroken power-law):

→ Low-energy excess... multicomponent flux? very soft spectrum?

→ Deficit of electron antineutrinos E>PeV... spectral break? flavor?

→ Tension with through-going muon data... multicomponent flux?

- Other inputs could affect the results: self-veto uncertainties, track misID energy dependence, muon background, hidden Glashow resonance contribution

# 4-YEAR DATA

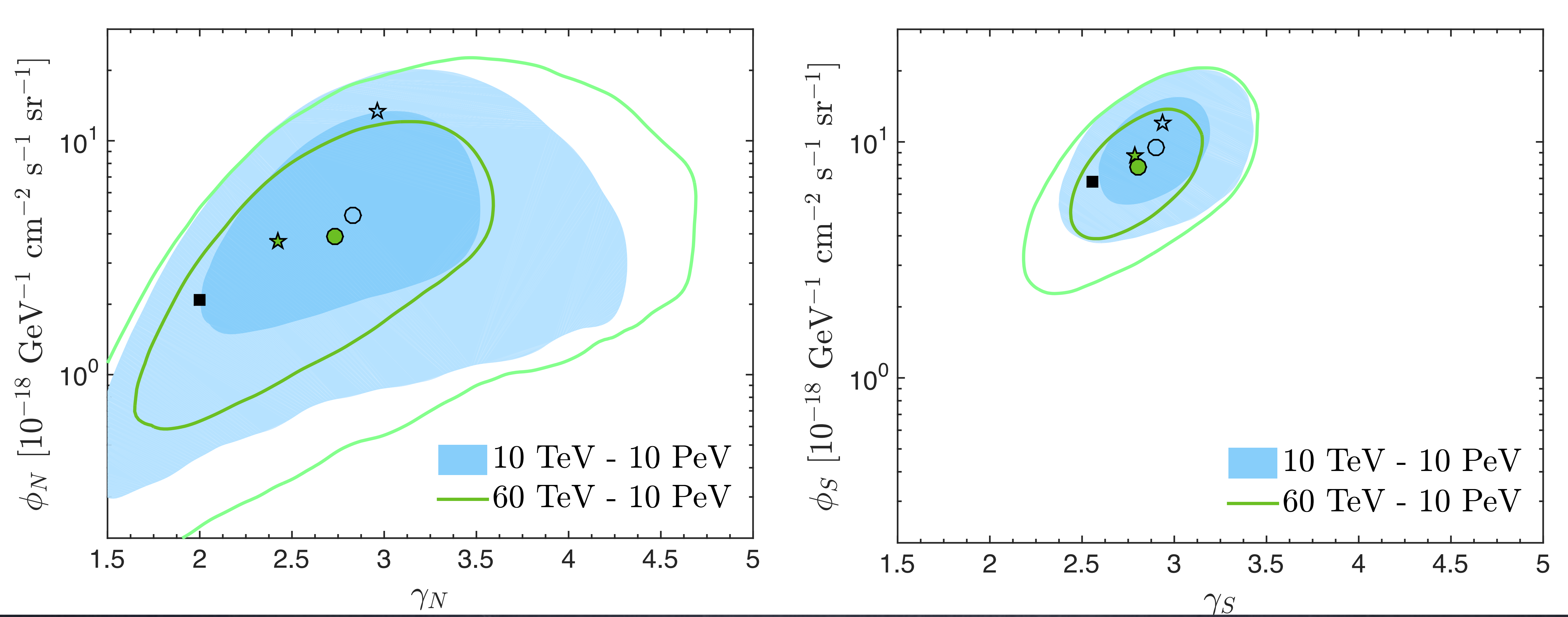
# UP/DOWN

Adding through-going muons: harder spectrum from the North at 1.1σ

M. G. Aartsen et al.[Icecube Collaboration], Astrophys. J. 809:98, 2015

## UPGOING NEUTRINOS

## DOWNGOING NEUTRINOS




A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# 4-year data

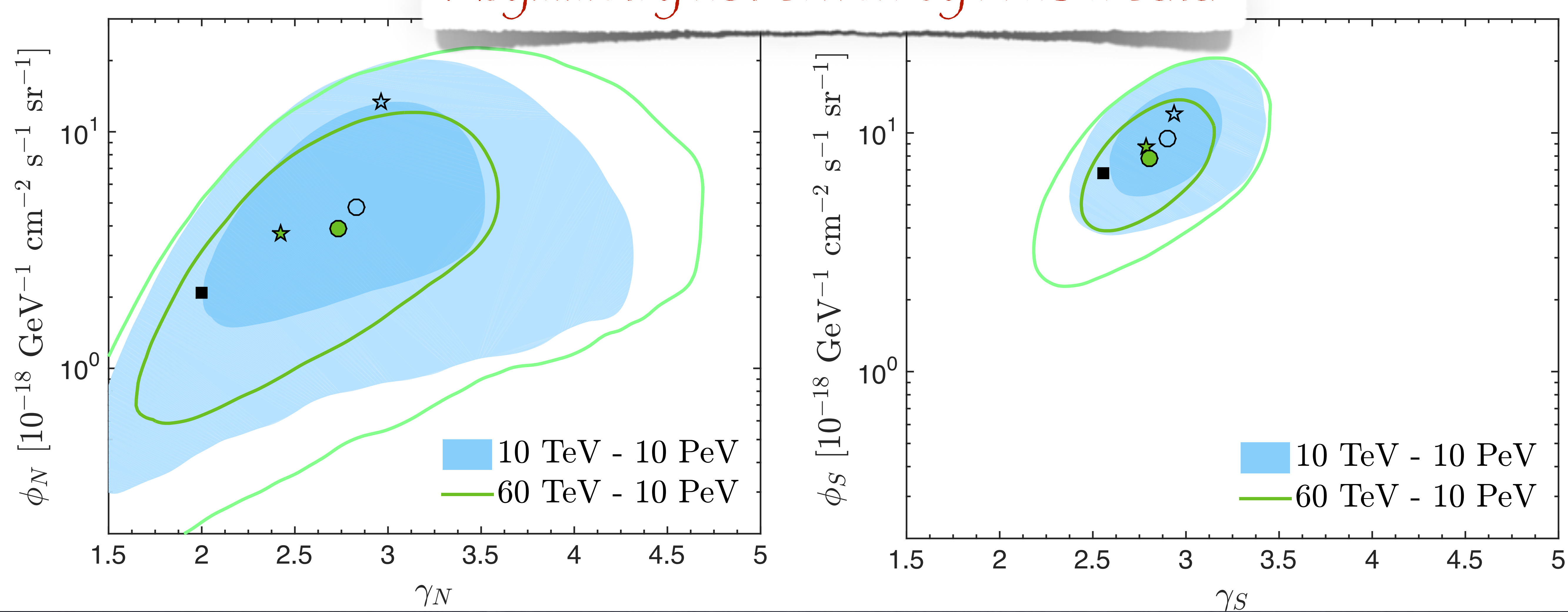
# Up/down

Adding through-going muons: harder spectrum from the North at 1.1σ

M. G. Aartsen et al. [Icecube Collaboration], Astrophys. J. 809:98, 2015

**Upgoing neutrinos** **Downgoing neutrinos**

Asymmetry not driven by HESE data



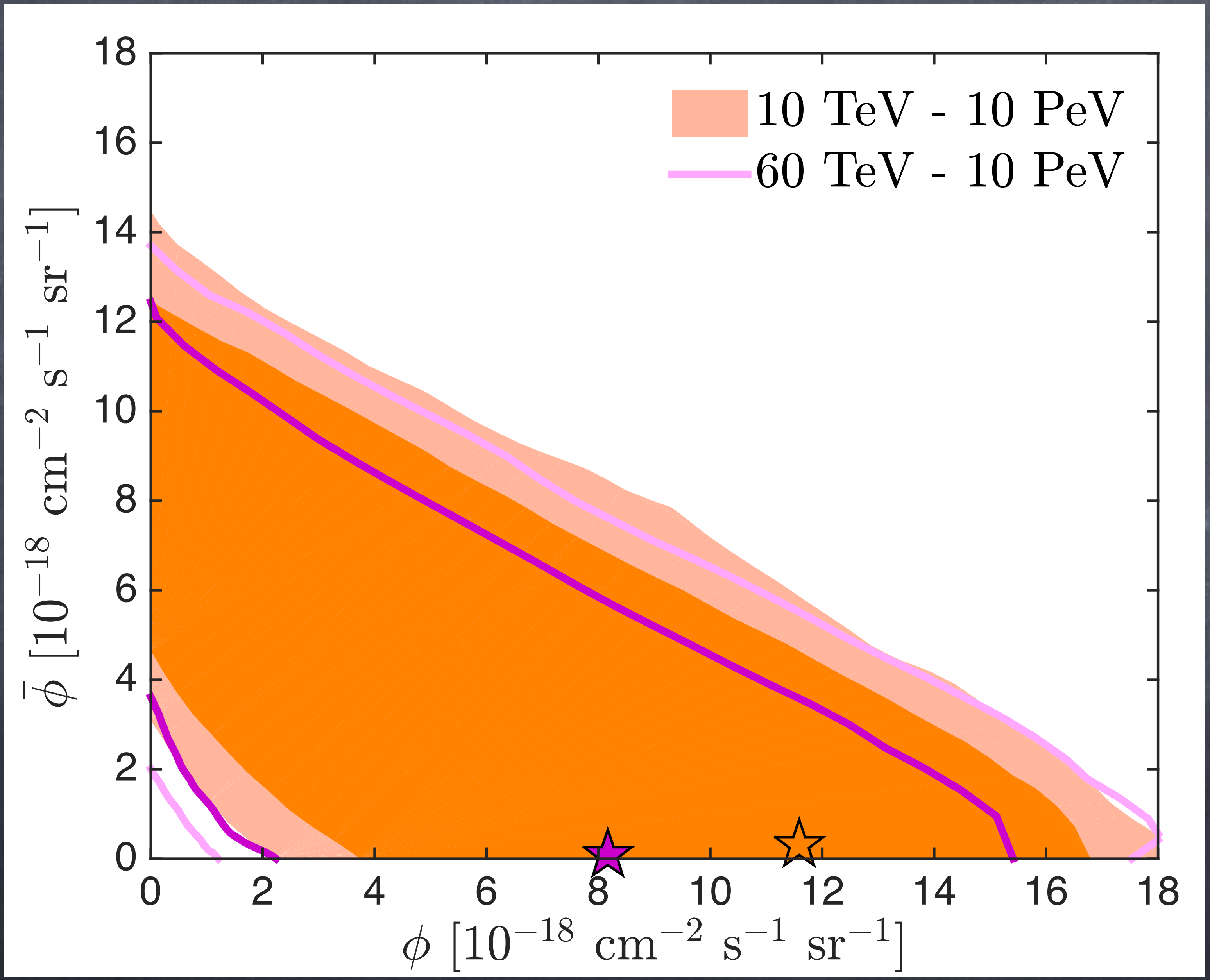

A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

# Neutrino/antineutrino

4-year data

Important with higher statistics

H. Nunokawa, B. Panes and R. Z. Funchal, JCAP 1610:036, 2016




A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016

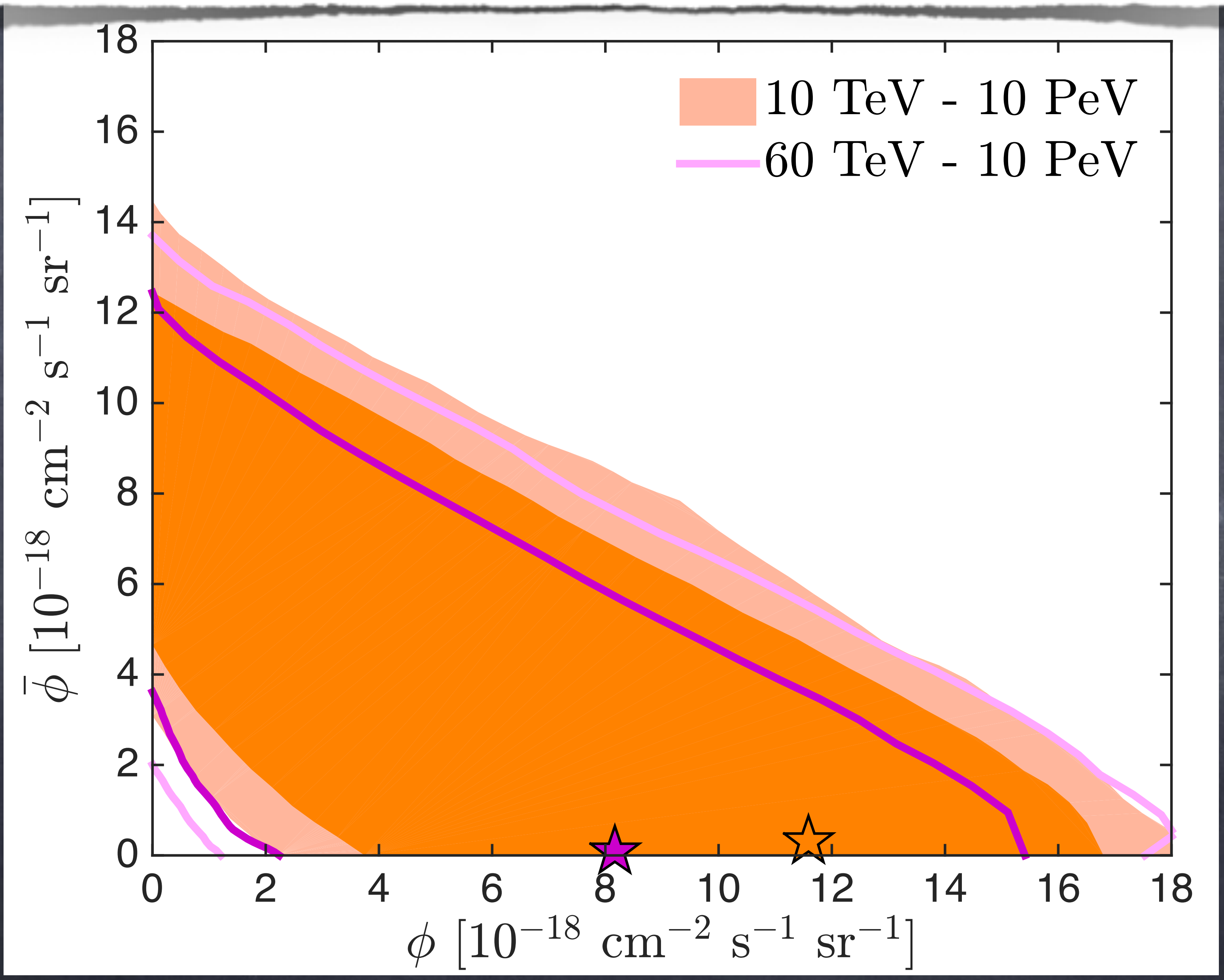
# Neutrino/antineutrino

Important with higher statistics

H. Nunokawa, B. Panes and R. Z. Funchal, JCAP 1610:036, 2016

4-year data

Strong correlation: too early to reach any conclusion




A. C. Vincent, SPR and O. Mena, Phys. Rev. D94:023009, 2016